รายงานโครงการวิจัยฉบับสมบูรณ์

Research Report

ระบบรับ-ส่งแบบไร้สายผ่านแสงสำหรับการสื่อสารข้อมูลความเร็วขนาดปานกลาง

Free-Space Optical Transceiver for Medium-Rate Data Communications

โดย

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ได้รับทุนอุดหนุนการวิจัยจากรายได้ คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์

ประจำปีงบประมาณ 2547

บทคัดย่อ

ระบบรับ-ส่งไร้สายผ่านแสงแบบฟูลดุปเพลกส์ความเร็ว10เมกกะบิตต่อวินาที ประกอบด้วยสามส่วนหลักคือวงจรตัวส่ง, วงจรตัวรับ และ วงจรเชื่อมต่อ ตัวกำเนิดแสงอาศัยไดโอดเปล่งแสงHPWT-BD00-E4000ซึ่งกำเนิดแสงสีแดงความยาวคลื่น635นาโนเมตร ลำแสที่ส่งออกมาถูกบีบเป็นลำแคบเหมาะกับการส่งระยะไกลด้วยเลนส์นูนขนาดเส้นผ่านศูนย์กลาง10 เซนติเมตร แสงที่มาถึงวงจรภาครับถูกรวมแสงโดยเลนส์ขนาดเดียวกันลงบนไดโอดรับแสง SFH2030 ระบบรับ-ส่งดังกล่าวสามารถทำงานได้อย่างถูกต้องโดยการทดสอบเชื่อมต่อคอมพิวเตอร์สองเครื่องที่ระยะห่างกัน300เมตร

คำสำคัญ: การสื่อสารไร้สายผ่านแสง,อีเทอร์เน็ต,ไดโอดเปล่งแสง, ไดโอดรับแสง, เลนส์

Abstract

A full-duplex 10Mbps optical transceiver for free-space optical data communications has been implemented. The transceiver comprises three important parts namely interface circuit, transmitter and receiver. The transmitter drives a super-flux HPWT-BD00-E4000 LED emitting 635nm visible red light. The outgoing light is collimated through 10-cm diameter lens. The incoming light signal is focused via 10-cm-diameter lens onto a photodiode SFH203. The received signal current from the photodiode is converted to signal voltage by resistance I-to-V converter, low-noise-amplifier, limiting amplifier and consequently delivered to the interface circuit. Link between two personal computers situated 300 meters apart has been successfully tested.

Keywords: Free-space optics, optical wireless, Ethernet, LED, photodiode, lens

กิตติกรรมประกาศ

คณะผู้วิจัยขอขอบคุณองค์กรและบุคคลต่อไปนี้ซึ่งมีส่วนสำคัญที่ทำให้งานวิจัยดำเนินไป ได้อย่างราบรื่น

คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์ ที่เอื้อเฟื้อเงินวิจัยสนับสนุน

ภาควิชาวิศวกรรมไฟฟ้า ที่เอื้อเฟื้อสถานที่และอุปกรณ์ในการทำวิจัย

Karel Kulhavy ที่ให้แนวคิดและคำแนะนำในการสร้างโครงงานนี้

นักศึกษาภาควิชาวิศวกรรมไฟฟ้าที่ช่วยเหลือในการทดสอบ

คณะการจัดการสิ่งแวดล้อมที่เอื้อเฟื้อสถานที่ในการทดสอบระบบรับ-ส่งต้นแบบ

คุณอุบลรัตน์ กำเนิดเพชร ที่คอยช่วยเหลือจัดการงานด้านเอกสาร,บัญชีและการเงิน รวมถึงการประสานงานโครงการวิจัยในหลาย ๆด้าน

คณาจารย์ในภาควิชาวิศวกรรมไฟฟ้าที่ให้คำปรึกษาในหลาย ๆด้าน

คุณมุทิตา อคุสุวรรณ ที่อำนวยความสะดวกในการจัดส่งวัสดุจากประเทศอังกฤษ

คุณภมรพล ชินะจิตร ที่อำนวยความสะดวกในการจัดส่งวัสดุจากประเทศสหรัฐอเมริกา

ขอขอบคุณคณะกรรมการผู้ทรงคุณวุฒิที่เสียสละเวลาอันมีค่าในการอ่านรายงานและ ความคิดเห็น ข้อเสนอแนะต่าง ๆ ในการทำงานวิจัยชิ้นนี้

คณะผู้จัดทำ

คำนำ

รายงานฉบับนี้นำเสนอผลงานการวิจัย "ระบบรับ-ส่งแบบไร้สายผ่านแสงสำหรับการสื่อสารข้อมูลความเร็วขนาดปานกลาง" (Free-space optical transceiver for medium-rate data communications) ซึ่งได้รับทุนวิจัยสนับสนุนจาก คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์ งานวิจัยดังกล่าวดำเนินงาน ณ ภาควิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์ เป็นระยะเวลาประมาณ 12 เดือน ได้ผลลัพธ์คือตัวรับ-ส่งต้นแบบซึ่งสามารถเชื่อมโยงเครือข่ายอีเทอร์เนตแบบไร้สายผ่านแสงในลักษณะสองทิศทางพร้อมกัน (Full duplex) ด้วยความเร็ว 10 เมกกะบิตต่อวินาทีภายในระยะทาง 300 เมตร โดยการออกแบบได้เน้นการใช้อุปกรณ์ราคาถูกและสามารถจัดหาซื้อได้ภายในประเทศ เพื่อเปิดโอกาสให้ผู้สนใจทั่วไปสามารถนำระบบต้นแบบที่นำเสนอนี้ไปพัฒนาและสร้างขึ้นมาใช้งานได้ด้วยตัวเองโดยไม่จำเป็นต้องมีความรู้ความชำนาญทางด้านอิเล็กทรอนิกส์ขั้นสูง งานวิจัยดังกล่าวได้รับรางวัลชมเชยจากการประกวดรางวัลนวัตกรรมแห่งประเทศไทย2548 (Thailand Innovation Awards 2005) สาขาวิศวกรรมศาสตร์และเทคโนโลยี และได้เข้าร่วมแสดงผลงานในงาน IRPUS48 ของสำนักงานกองทุนสนับสนุนการวิจัย (สกว.)

คณะผู้วิจัยหวังว่างานวิจัยดังกล่าวจะมีประโยชน์ในการนำไปใช้งานได้จริงและเชื่อว่ายังสามารถพัฒนาให้มีประสิทธิภาพดียิ่งขึ้นทั้งในด้านระยะทางและอัตราความเร็วในการรับ-ส่ง รวมถึงการพัฒนาเป็นสินค้าเพื่อผลิตจำหน่าย

คณะผู้จัดทำ

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List of abbreviations and symbols

AC	Alternating Current
BJT	Bipolar Junction Transistor
bps	bit per second
dB	decibel
DC	Direct Current
EMI	Electromagnetic Interference
FET	Field Effect Transistor
FSO	Free-Space Optics
Gbps	gigabits (10^9 bits) per second
g_m	transconducatance
IC	Integrated Circuits
IEEE	Institute of Electrical and Electronic Engineering
LAN	Local Area Network
LED	Light Emitter Diode
lm	lumen
LNA	Low-Noise Amplifier
m	meters
m	milli (10^{-3})
Mbps	megabits (10^6 bits) per second
MHz	Megahertz (10^6 Hertz)
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
nm	nanometers (10^{-9} meters)
PCB	Printed Circuit Board
RF	Radio Frequency
Rx	Receiver
Si	Silicon
TIA	Transimpedance Amplifier
Tx	Transmitter
UTP	Unshielded Twist Pair
V	Volt
Vp-p	peak-to-peak voltage
ω	Angular frequency

Chapter 1 Introduction

1.1 Background

Today's information economy depends on the transmission of data, voice and multimedia across telecommunication networks. This high bandwidth demand is driven by the increasing commercial use of the Internet, intranet, videoconferencing, and voice over IP. Such a worldwide demand for broadband communications is being met in many places by installed fiber-optics networks. Amid the pervasive talk about the promises of the information economy, it's easy to overlook the logistical challenges of delivering the necessary infrastructure to ensure everyone who wants connectivity is connected—regardless of where they live. Projected growth in customer demand for bandwidth will go wanting without connectivity, and the real challenge for fully realized networks is to create connections despite the very real physical and economic obstacles presented by today's modern cities. The rewards for providing these connections are the likelihood of recouping previous investments in the fiber-optics network core/backbone—and establishing customer reliance on high-bandwidth networks for continued economic growth.

1.2 The last-mile problem

Meeting projected bandwidth needs, however, depends on customers having access to optical networks. This has yet to fully occur in the metropolitan areas, which remain a relatively untapped bandwidth access market where an estimated 7 percent to 10 percent of end-users are connected to fiber-optic network. Imagine a city water distribution system that does not deliver water to buildings and residences because its pipes do not reach far enough. Much the same situation exists for America's high-speed data-transfer network. The multibillion-dollar optical-fiber backbone that was built to bring truly high-performance multimedia services to office and home computers across the nation has come up a bit short--for nine out of 10 U.S. businesses with more than 100 workers, less than a mile short. This link shortage is widely known as a "last-mile" problem, which seriously limits the availability of high bandwidth connections across networks. As depicted in Fig.1.1., studies show that less then 5% of all buildings in the US have a direct connection to the very high speed (2.5-10 Gbps) fiber optic backbone, yet more than 75% of businesses are within 1 mile of the fiber backbone. Most of these businesses are running some high speed data network within their building, such as fast Ethernet (100 Mbps), or Gigabit Ethernet (1.0 Gbps). Yet, their Internet access is only provided by much lower bandwidth technologies available though the existing copper wire infrastructure (T-1 (1.5 Mbps), cable modem (5 Mbps shared) DSL (6 Mbps one way), etc). The last mile problem is to connect the high bandwidth from the fiber optic backbone to all of the businesses with high bandwidth networks

At one point, many telecommunications industry leaders and technology observers dreamed of all-fiber networks. But this vision is impractical for several reasons. The process of laying fiber in cities is time-consuming and often prohibitively expensive. Traditional copper wires and coaxial cables connecting buildings to telephone and cable television systems simply do not possess the gigabit-per-second capacity necessary to carry advanced bandwidth-intensive services and applications, whereas optical-fiber bridges needed to connect millions of users to the optical-fiber backbone would cost too much to install (between $100,000 and $500,000 a mile).

Deciding how best to complete high-bandwidth connections across networks is one of the great quandaries of the information age, and choosing which technologies to deploy to complete network connections will depend on costs and reliability. A combination of high-capacity access technologies provides the most cost efficient and reliable solutions for addressing both primary connections and backhaul.

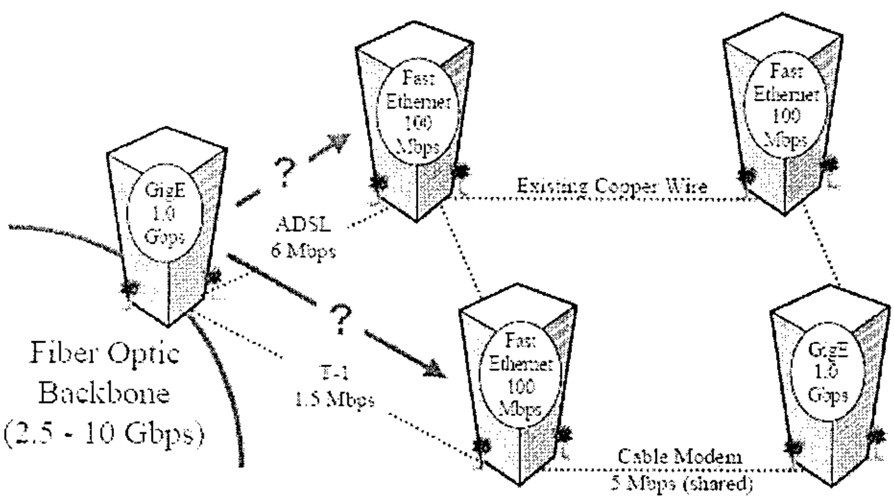


Fig.1.1: *The last mile problem* [1.1].

Bridging the last mile

There are a few possible solutions that might be employed to bridge the gap:

- DSL and cable modems can, to some extent, take advantage of existing wired networks; however, they cannot provide true broadband services in a deterministic way. DSL technology is plagued by the actual topology of the copper to which it is attached, and is limited in distance (from the central office) and capacity (several Mbps). Cable modems enjoy higher capacity, yet the channel is shared and the amount of bandwidth at any given time is not guaranteed.
- Radio frequency (RF) wireless systems can be used as a solution to the bridging problem, but they are limited in data rate because of the low carrier frequencies involved. In addition, because "broadcast" technology is generally regulated, it must operate within allocated regions of the spectrum. Spread-spectrum RF, especially emerging ultra-wideband (UWB) technology, can avoid spectrum allocation provided transmit powers are kept very small (to avoid interference problems), but this generally limits the range to a few tens of meters. Unlicensed wireless RF technologies are also limited in capacity, and carriers are reluctant to install systems that might have interference issues. Licensed wireless RF technologies can provide very high capacity, but the nonrecurring initial capital expenditures for spectrum licenses usually make the business model very difficult to implement. Additionally, in any given city the licenses permit only two carriers to participate.
- Fiber optic is a choice that can meet the Gbps data-rate demand but its main problems stem from high cost of installation and long time of deployment before the system can be effectively in use. Street trenching and digging are not only expensive, they cause traffic jams (which increase air pollution), displace trees, and sometimes destroy historical areas. For such reasons, some cities, such as Washington, D.C., are considering a moratorium on fiber trenching. Others, like San Francisco, are hoping to limit disruptions by encouraging competing carriers to lay fiber within the same trench at the same time. Things have reached this state because carriers spent billions of dollars to increase network capacity in the core, or backbone, of their networks, but have provided less lavishly at the network edges.
- Free-space optics (FSO) or optical wireless as illustrated in Fig.1.2 is thought by many experts to have the best chance of succeeding. Newly revived over the past few years after having been invented in the 1970s, FSO relies on low-power infrared laser transceivers that can beam two-way data at gigabit-per-second rates. In many respects, free space optical communications can be the offspring of a happy marriage of free space RF and guided wave fiber optical approaches. It can provide many of the benefits

of fiber optical communications for usage in wireless applications. In particular, FSO is well suited for providing high bandwidth point-to-point wireless links.

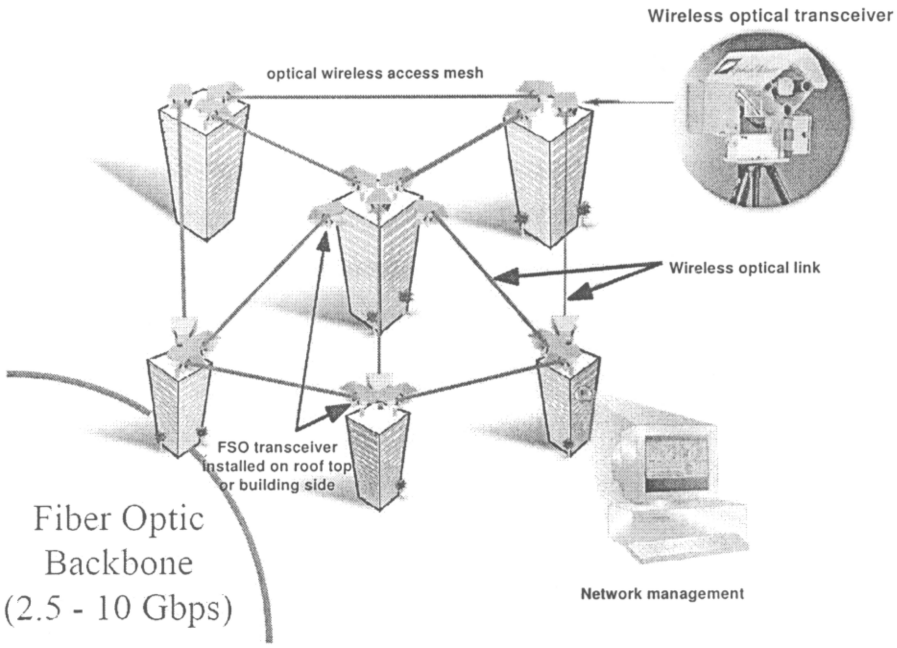


Fig.1.2: *Last-mile connectivity by wireless optical link* [1.1]

Advantages of FSO

- Optical wireless and fiber also integrate seamlessly, and because optical wireless equipment is simple and easily installed, the technology can bridge optical network gaps effectively. Their integration offers several technological advantages. First, fiber optics and optical wireless solutions share several characteristics. Optical wireless solutions can use the same optical transmission wavelengths as fiber optics (850nm or 1550 nm). Second, optical wireless solutions and fiber can utilize the same system components such as lasers, receivers and amplifiers. Third, both fiber and optical wireless can transmit digital information using a range of protocols. Fourth—and critically important in meeting technological demands—optical wireless delivers the bandwidth (up to 2.5Gbps) necessary to complement fiber networks.
- The business advantages of optical wireless for network extensions include deployments at an average of one-fifth the cost of fiber-optic cable and in one-tenth the time. Optical wireless systems are a flexible investment that can be re-deployed to meet changing customer needs. FSO has a major time-to-market advantage over fiber. Fiber builds often take 6 to 9 months, whereas an FSO link can be operational in a few days. Table 1.1 shows a cost comparison among established broadband access technologies and optical wireless.

- Installing optical wireless solutions to complement fiber enables service providers to secure customers in a specific location first before installing the system to bridge to the fiber network, providing optimal alignment between capital expenditure and income.
- An added benefit from the use of FSO is relief from the regulatory, licensing, and frequency management and co-ordination issues encountered in implementing RF systems. FSO systems are not currently subject to regulation or control by any frequency management organization, like the FCC or ITU.
- FSO system is typically implemented as a narrow-beam point-to-point connection; there is little likelihood of interference. Moreover, the system is inherently secure and resistant to taps. Intrusion to the communication FSO channel can easily be detected.

Table 1.1: *Cost comparison among established broadband access technologies and optical wireless. The monthly costs for the RF and optical systems correspond to full depreciation of the equipment costs over three years [1.1]*

Access Medium	**Speed (Mbps)**	**Equipment Cost ($)**	**Cost per Mbps ($)**	**Monthly Cost ($)**	**Cost/Mbps/Month ($)**
Dial-up	0.056	--	--	20	357
Satellite (DBS)	0.4	--	--	50	125
Cable Modem	1.5	--	--	50	33
DSL (min)	0.144	--	--	49	340
DSL (max)	8	--	--	1200	150
T-1	1.54	--	--	300	195
T-3	45	--	--	3000	67
RF Median price, 6 vendors	155	45,000	290	1250	8
Optical wireless SONAbeam 155*	155	20,000	130	555	4

* This product operates at 155 Mbps at distances up to 2 km, depending on fog conditions.

With the aforementioned advantages of FSO listed above, it is little wonder, therefore, that nearly a dozen of companies are developing FSO technology. If things go as proponents predict, the industry could grow from approximately $120 million in 2000 to more than $2 billion annually by 2006, according to a study conducted by the Strategis Group, a Washington, D.C.-

based telecommunications research firm. It is expected that FSO systems will become more and more common sights in metropolitan area. It is thus crucial for academic and research communities in Thailand to catch up with the technology. The project would bring benefits in terms of system learning and understanding, design experience where there are so many interesting technical challenges awaiting to be tackled.

Disadvantages of FSO

Rather than replacing optic fiber or other high-bandwidth communication systems, FSO is considered as a significant complement to the existing infrastructures. There are number of disadvantages that prevent FSO

- Line of sight is always necessary for the FSO, obstruction by various means (birds, building, trees) prohibit the deployment of the system or cause the service interruption.
- Weather conditions can severely affect the system performance to non-operating level. Susceptibility to fog has slowed the commercial deployment of free-space optical systems. It turns out that fog (and, to a much lesser degree, rain and snow) considerably limits the maximum range of an FSO link. Fog causes significant loss of received optical power. This optical attenuation factor scales exponentially with distance. In moderately dense fog, for example, the optical signal might lose 90 percent of its strength every 50 meters. This means that 99 percent of the energy is expended over a span of 100 meters and that 99.9 percent is dissipated after travelling 150 meters. Thus, to be practical, a free-space optical link must be designed with some specified "link margin," an excess of optical power that can be engaged to overcome foggy conditions when required.
- The FSO beams tend to lose alignment due to the relative movement of buildings and therefore may lead to link outages. This may be taken care by increasing the beam divergence. However, this could significantly reduce the operating range. A more sophisticate solution is by integrating an auto-tracking system and this would normally increase cost of the system.

1.3 FSO historical background and design issues [1.1] - [1.14]

The concept of free-space optics (FSO) or optical wireless communications has been used for millennia, examples including smoke signals and semaphore flags. In 1880, Alexander Graham Bell patented the photophone, which modulated light reflected from the sun with a voice signal and transmitted that across free space to a solid-state detector (Fig.1.3). Thus was born the first Free Space Optics (FSO) link. Given that Bell described the photophone as "*the greatest invention I have ever made; greater than the telephone*," we can see that the hype for FSO is also nothing new. The electrically powered optical technologies referred to by the term "optical" or "electro-optical" began with the introduction of the laser in 1960, which enabled the transmission of digital information as pulses of light.

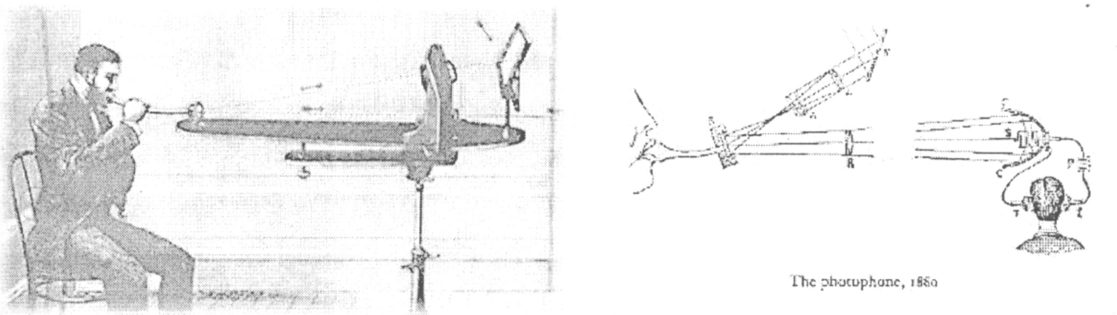


Fig.1.3: *Alexander Graham Bell's Photophone, 1880.*

Recent developments in FSO technology target telecommunications improvements for Metropolitan Area Networks (MANs), but the technology has its roots in government applications dating back to World War I when military units and covert agencies needed secure communication systems that did not require cable and could withstand intentional interference, also known as "radio jamming". Portability of these early FSO devices was a hallmark and made them particularly valuable to military personnel who needed secure communications equipment that was simple to set up, transmit information and move from location to location. Additional optical communications developments occurred during World War II, and post-war economic restructuring led to further telecommunications technology progress. While electronics innovations such as the transistor and integrated circuits enabled post-war telecommunications progress, the laser's launching of electro-optical communication fuelled research and development of advanced optical communications using the only medium for laser transmission available then to military and aerospace industry physicists: the atmosphere, or "free space," hence the term free-space optics. Research and application of free-space optics continues to thrive in the aerospace industry to this day for applications beyond commercial and private telecommunications networks. Today's commercially deployed optical wireless solutions are the result of a culmination of FSO technology advancements. There are many vendors offering FSO systems in today's world market such as: MRV, Lightpointe, AirFiber, fSONA, Canon, Terabeam providing services across the globe for law firms, finance corporations, government and private sectors, academic campus, service providers.

Free-space optics system design Issues

- *Subsystem:* The FSO will be discussed below.
- *Link Equations*: There are various factors in the system that affect link equation. The relative importance of each of these factors is compared in realistic weather conditions
- *Comparison Link Budgets:* Link budgets for point designs that are offered in the marketplace. Most of the data for these designs is available via the vendor's data sheets or from the world wide web. If an assumption is made about a component, that fact is noted.
- *Availability*: Actual weather statistics from nephelometers and some vendor's free-space optical communications systems should be used to compute link range as a function of availability for carrier-class numbers (99.9% or better).
- *Theoretical Maximum Range*: A straw-man design should be used to compute the maximum range in 200 dB/km attenuation conditions. Since this is not obtainable, it sets an upper limit on range for free-space systems. The maximum range as a function of availability has to be considered for several cities.
- *Bit Error Rate, Data Rate, and Range*: Theoretical curves of BER and data rate have to be investigate to see whether reducing data rate or relaxing BER constraints does or does not significantly increase the maximum range in realistic weather scenarios.
- *1550 nm versus 785 nm wavelengths*: The debate over propagation characteristics of near infrared (IR) versus 1550 nm light should be resolved by curves generated by multiple scattering codes from visible through millimeter waves.
- *FSO Systems Enhancements*:
  - Tracking: the requirements for tracking systems in carrier-class free-space optics systems.
  - Physics of Scintillation: scintillation effects and techniques for mitigating the detrimental effects of scintillation.
  - Power Control and Eye safety: the benefits of power control for long-term laser reliability and eye safety.

FSO Subsystems

Fig.1.4 illustrates the major subsystems in a complete carrier-grade free-space optics communications system. This FSO transceiver system is the main focus of the project. The optical apertures on a free-space system can have an almost infinite variety of forms and some variety of function. They can be refractive, reflective, diffractive, or combinations of these. In Fig.1.4, the transmit, receive, and tracking telescopes are illustrated as separate optical apertures; there are several other configurations possible where, for example, a single optic performs all three functions thereby saving cost, weight, and size. On the transmit side, the important aspects of the optical system are size and quality of the system. Size determines the maximum eye-safe laser flux permitted out of the aperture and may also prevent blockages due to birds. Quality, along with the f-number and wavelength, determine the minimum divergence obtainable with the system. On the receive side, the most important aspects are the aperture size and the f-number. The aperture size determines the amount of light collected on the receiver and the f-number determines the detector's field of view. The tracking system optics' field of view must be wide enough to acquire and maintain link integrity for a given detector and tracking control system.

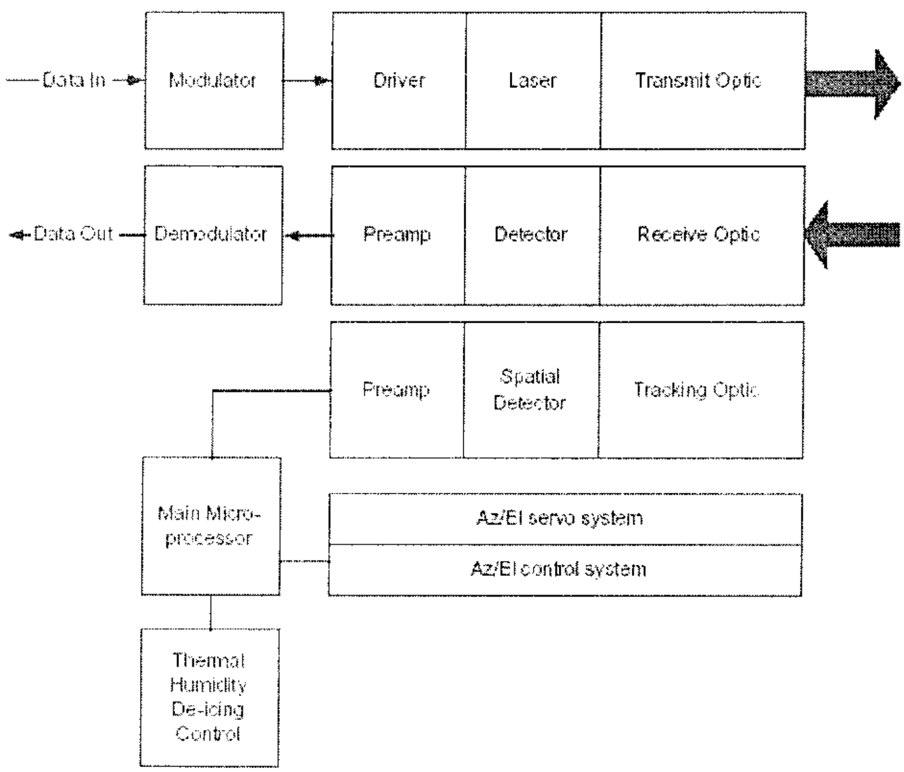


Fig.1.4: *Free-Space Optics Major Subsystems.*

Several means are available for coupling the laser to the output aperture. If a discrete diode is used, the diode is usually micro-lensed to clean up the astigmatism of the output beam and then is free-space coupled to the output aperture by placing the laser at the focus of the output aperture optical system. The coupling system is very similar for fiber lasers because the core of the fiber laser and the output aperture of a Fabry-Perot laser have similar sizes. The distance from the laser aperture to the output aperture must be maintained such that the system divergence remains in specification over the temperature ranges encountered in an outdoor rooftop environment. This can be accomplished with special materials and/or thermal control.

Diode lasers are driven with a DC bias current to put the devices above threshold, and then, on top of that, are modulated with an AC current to provide, for example, on/off keying (OOK) for data transmission. For lasers with output powers below approximately 50 mW, off-the-shelf current bias and drive chips are available; for higher power lasers, custom circuits or RF amplifiers are generally used.

The receive detector is coupled to the receive aperture through either free-space or fiber. Depending on the data rate and optical design alignment, tolerances can be extremely restrictive. For example, for data rates to 1.25 Gbit/s, detectors with relatively large active areas (500-micron diameter) can be used, making alignment to the receive aperture fairly straightforward. For fiber-optic coupling into multimode fibers, the correct size is about 63 microns in diameter, which makes alignment much tougher. The use of special materials or controls is required in this case, however, coupling is more modular.

Detectors are generally either PIN diodes or avalanche photodiodes (APD). For carrier-class free-space optics systems, an APD is always advantageous since atmospheric induced losses can reduce received signals to very low levels where electronics noise dominates the signal-to-noise (SNR) ratio. Of course the APD must be capable of meeting the system bandwidth requirements. Usually a trans-impedance amplifier is used after the detector because in most cases they provide the highest gain at the fastest speed.

If CCD, CMOS, or quad cell detectors are used as tracking detectors, these relatively large area devices are easy to align to the tracking optics. However, care must be taken in manufacture to co-align these optics with the transmit and receive optical axes. For building-mounted free-space optical systems, the tracking bandwidth can be very low— sub-hertz— because the bulk of building motion is due to the building's uneven thermal loading and these effects occur on a time scale of hours. For systems that are to be mounted on towers or tall poles, the tracking bandwidth should be higher—most likely on the order of several hertz at least—to remove wind-induced vibrations.

Acquisition systems can be as crude as aligning a gunsight to very sophisticate GPS-based, high accuracy, fully automated systems. The choice of this subsystem really depends on the application and number of devices to be put into a network.

1.4 Research aims

The ultimate aim of the project is to design and analysis free-space optical transceivers for medium-speed data communications (above 10Mb/s) over a distance of 300m to connect between buildings within the campus. This is an important starting point for a commercial 1-Gbps FSO laser transceiver project which is currently being applied for university research grant. In order to achieve this aim, there are objectives that need to be accomplished to constitute to the final goal as follows:

- Circuits and systems design, modelling, analysis and simulation which include atmospheric modelling, budget link, and combining various electronics and optoelectronics components for the whole FSO systems simulations.
- Transmitter design and receiver design based on eye-safety LEDs emitting 635nm velength.
- Transceiver (TRx) design involves integrating the transmitter and receiver together as a single system.
- Integrate the prototype into the existing computer communications system and test the FSO prototype viability. There is an interface part that has to be able to communication seamlessly between the transceiver and the computer (or hub, etc.) network card.

Possible applications

- The working prototypes can be employed in various applications related to moderate data rate communications from point to point. Applications ranging from hospitals, banks and telecommunications companies to municipal and military installations. For private corporate networks, FSO systems provide a very high bandwidth link between sites without the recurring costs of leased lines. For high bandwidth applications such as videoconferencing, the system provides new alternatives to installing fiber optic cable between sites where it is very expensive or impossible to lay. For temporary network connectivity needs, such as at exhibitions, conventions, sporting events, or disaster recovery, high bandwidth links can be easily and quickly provided using portable FSO systems. In addition, the systems are also used as high-speed wireless backup for fiber optic cable and as "Last Mile" solutions, connecting customer sites to fiber backbones. Application examples are displayed in Fig.1.5 – Fig.1.9 (from http://www.lightpointe.com):

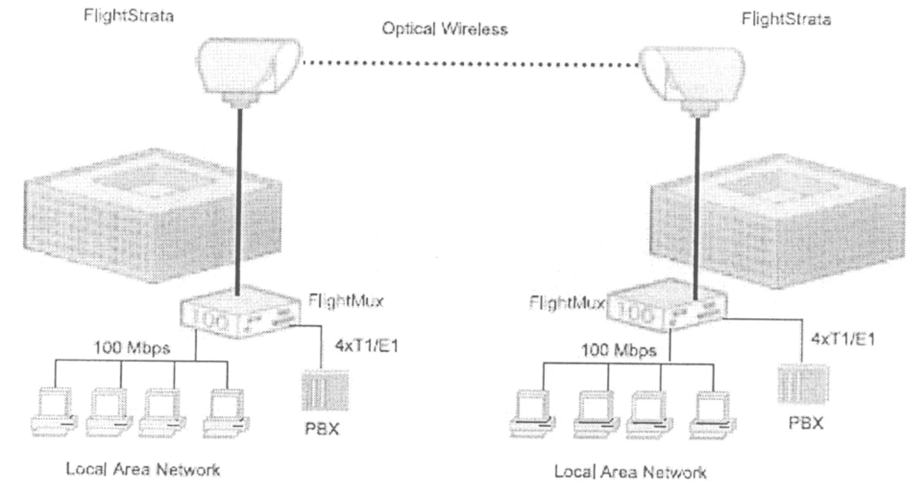


Fig.1.5: *Building-to-Building Connectivity with Optical Wireless (Voice and Data Network).*

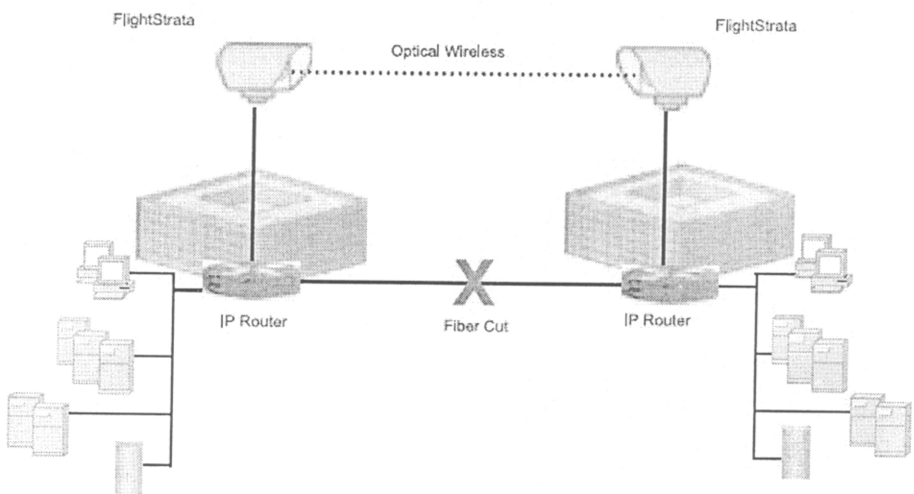


Fig.1.6: *Disaster Recovery with Optical Wireless.*

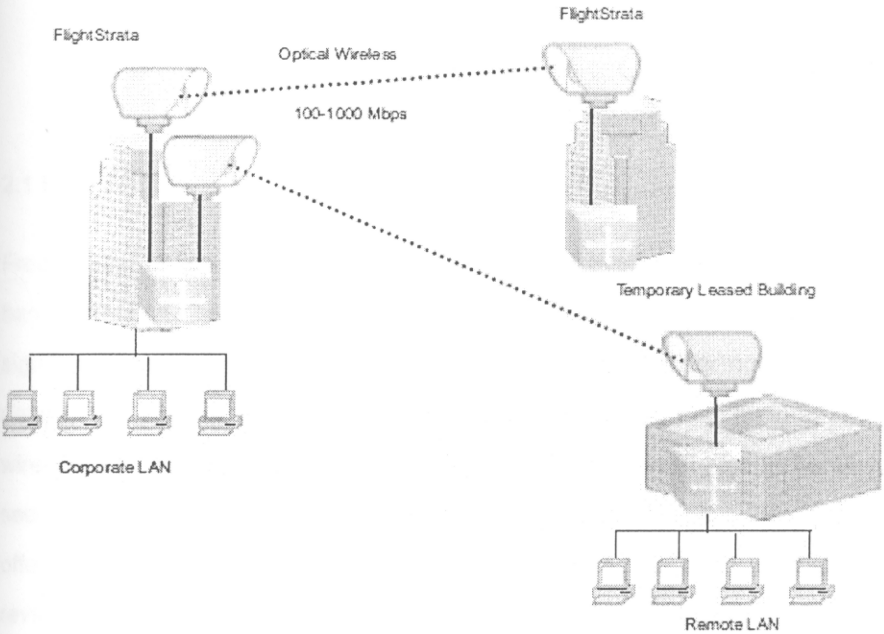


Fig.1.7: *Network Portability with Optical Wireless.*

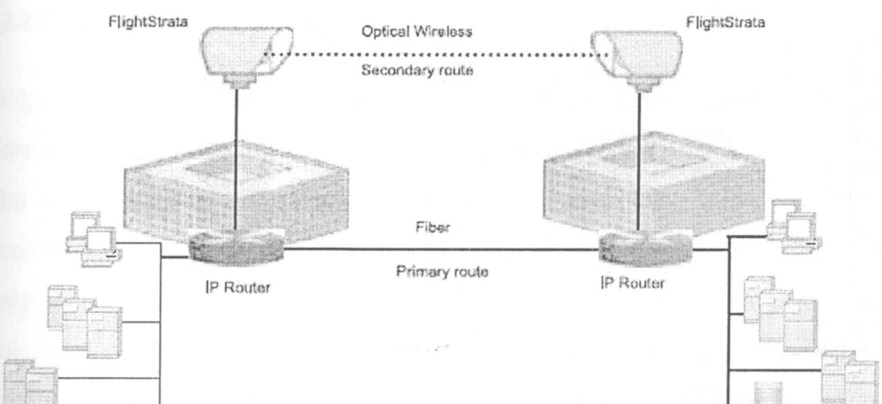


Fig.1.8: *Network Redundancy with Optical Wireless.*

Chapter 2 System Overview

2.1 Introduction

Free-space optics (FSO) or optical wireless prevails itself as a viable alternative for high bandwidth data networking and Ethernet, especially when the "last-mile problem" plays significant role in high-speed optical fiber link. Although fiber optics can provide high-bandwidth data link, it suffers greatly from high cost of installation and maintenance. On the other hand, wireless radio can meet the cost issue but the problems of limited bandwidth, licensing and link security do not make radio as a clear winning choice of the future. FSO systems however can offer the best of both worlds with no license required (at least for the time being). This chapter reviews important concepts, system building blocks and key optoelectronic components of the FSO transceiver whereas the detailed circuits will be given in the subsequent chapters.

2.2 FSO Structure

Fig.2.1 illustrates a simplest one-way FSO system comprising a transmitter and a receiver. An electrical signal coming from any information sources (such as computer network card) has to be converted into an optical domain before transmitting into free space. Electrical-to-optical conversion can be simply performed by utilising a light emitting diode (LED) which emits optical signal at particular wavelength. Note that it is not necessary to perform electrical signal modulation before carrying out electrical-optical conversion. In general the LED is switched by supplying signal current provided from an LED driver. On the receiving end, an optical-to-electrical conversion is achieved using a photodiode where it typically transforms optical signal into current. Such current is further converted into voltage signal by a transimpedance amplifier (TIA) before supplying to a limiting amplifier and subsequent stages. In this research an LED is justified instead of a laser diode mainly by low-cost consideration and the target data rate is not too high for an LED.

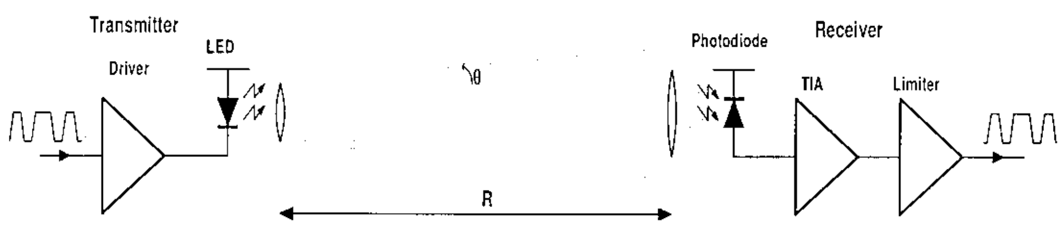


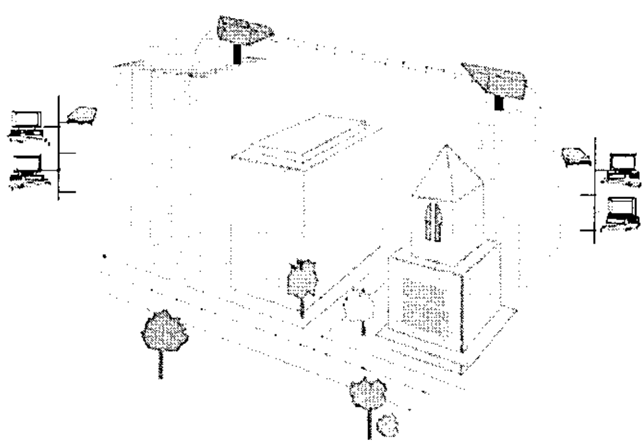
Fig.2.1: *Simple FSO system (one-way communication)*

Fig.2.2a depicts a typical point-to-point free-space optical communication system linking between two buildings. The receiving power P_{Rx} can be related to transmitting power P_{Tx} by [2.1]

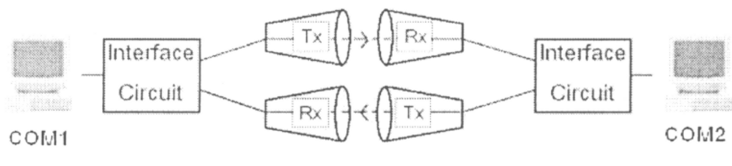
$$P_{R_x} = P_{T_x} \cdot \frac{A_{R_x}}{(\theta \cdot R)^2} \cdot \exp(-\alpha \cdot R) \tag{2.1}$$

where A_{Rx} is an optical receiver's area, R link range (in km), θ is a beam divergence (in radians) and α is an atmospheric attenuation (dB/km). The receiving power is linearly proportional to transmitting power and receiving area while atmospheric condition does strongly affect link integrity as indicated by factor α in (2.1). Parameters P_{Tx}, A_{Rx}, and θ can be controlled by designers to enhance the link range.

A typical FSO transceiver comprises receiver, transmitter and interfacing circuitry with collimating lens as shown in Fig.2.2b. When in operation, data signal from COM1 (as an example) Ethernet card enters the interfacing circuit, which transforms such signal into an appropriate form for the transmitter. The transmitter converts electrical signal into light and emit energy containing data signal into free space. The incoming light falls onto the receiver and is converted back to electrical domain before sending to interfacing circuit and eventually the Ethernet card of COM2. Light collimation is achieved by lens and it thus provides a reasonable link range. The data signal travelling in an opposite direction (from COM2 to COM1) also relies on the same concept.



(a)



(b)

Fig.2.2: *Typical FSO transceiver employing to link between two buildings*

Light transmission in free-space strongly depends on atmospheric condition as well as the light wavelength being employed as a carrier. Transmission dependence on wavelength is shown in Fig.2.3.

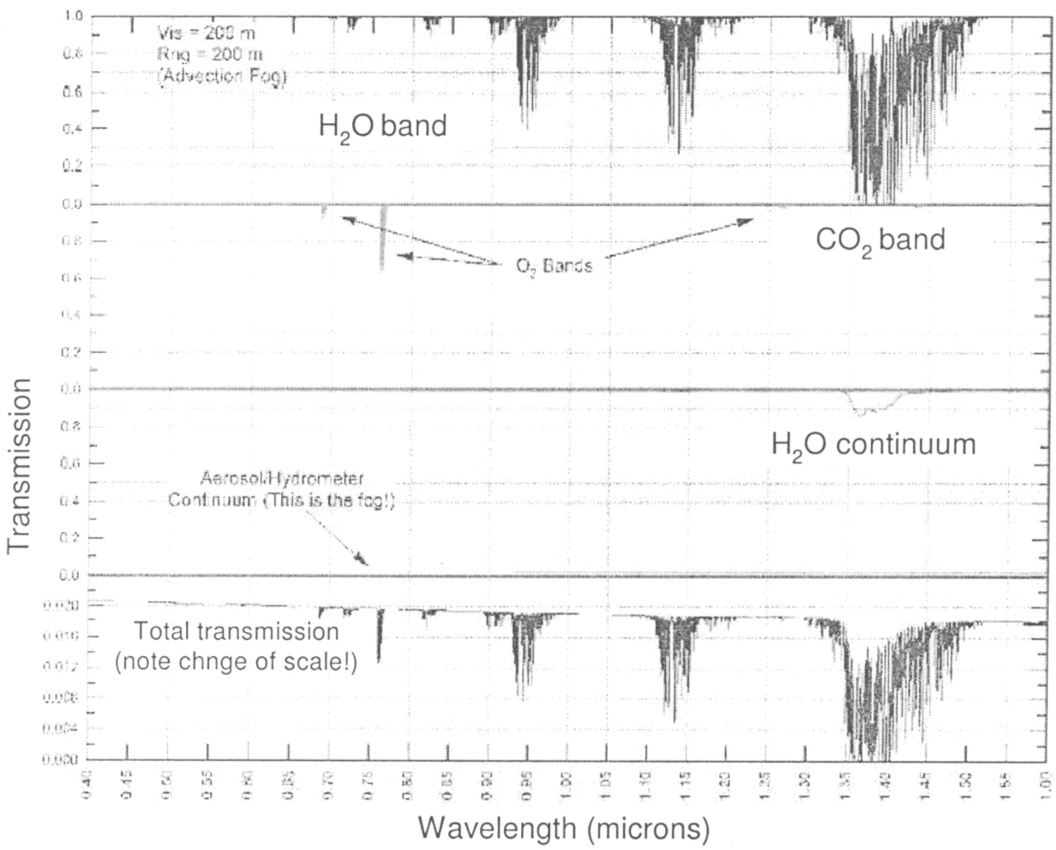


Fig.2.3: *Transmission efficiency as function of light wavelength*

Fig.2.3 suggests that a visible red light (630-650nm) can also render a reasonable atmospheric propagation compared to other wavelengths. A visible light also makes aiming more convenient than those wavelengths in infrared region. In today's market, manufacturers have been constantly improving quality of red LEDs in terms of higher radiating power, switching speed and low cost when compared to other visible LEDs, e.g. blue and green.

2.3 Light emitting diode properties

A red light-emitting-diode (LED) HPWT-BD00-E4000 from Lumileds is selected as the light source for the transmitter. The led provide a visible red light of 635nm as indicated in Fig.2.4. With the propagation characteristic in Fig.2.3, at wavelength of 635nm the transmission quality can be practically utilised as a carrier's operating wavelength for the free-space optical link.

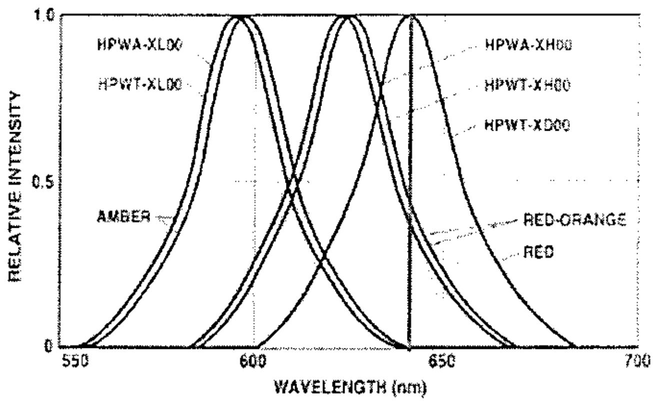


Fig.2.4: *HPWT-BD00-E4000 relative intensity characteristic* [2.1]

Half angle of HPWT-BD00-E4000 is 30° with typical total flux of 3.5lm (minimum at 2.5lm and maximum at 6.1lm) and the typical intensity of 8.0cd (minimum at 5.0cd and maximum at 12.2cd). Regarding LED switching speed, HPWT-BD00-E4000 possesses a parasitic capacitance of 40pF with time constant of 20ns which is sufficient for data switching at 10Mbps. Voltage and luminous flux vs current characteristics of HPWT-BD00-E4000 are as shown in Fig.2.5 and Fig.2.6 respectively.

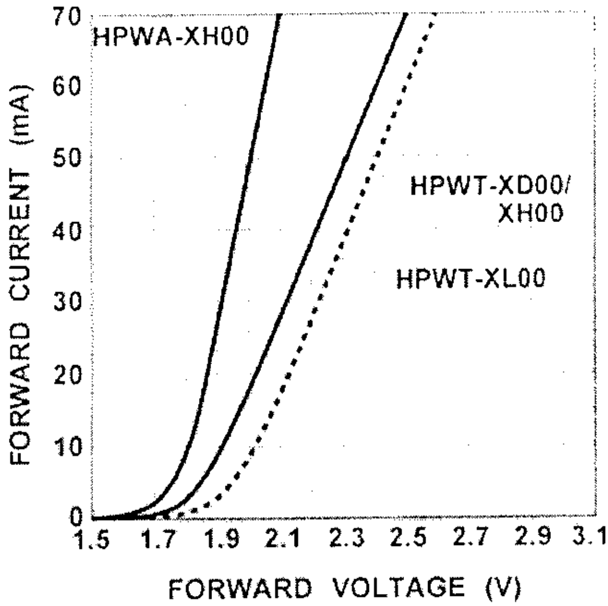


Fig.2.5: *LEDs' V-I characteristics* [2.1]

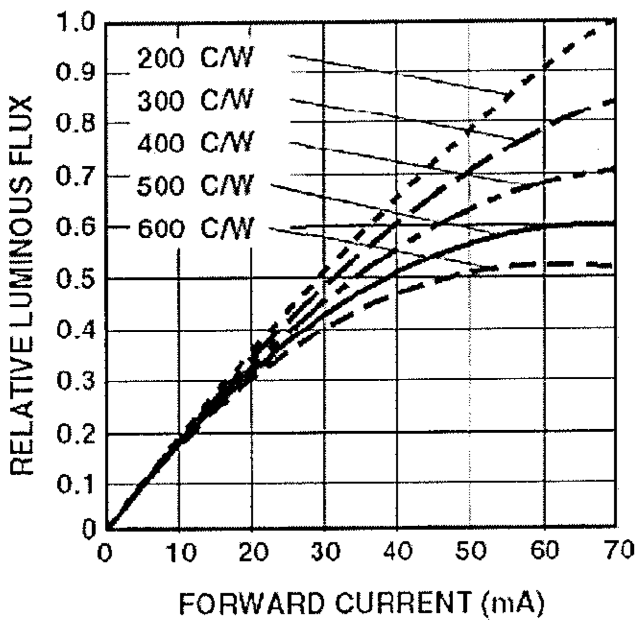


Fig.2.6: *LEDs' luminous flux vs forward current characteristics* [2.1]

2.4 Photodiode properties

On the receiver part, an optical-to-electrical conversion is accomplished by employing an inexpensive Si PiN photodiode (PD) SFH2030 from Siemens whose relative sensitivity S_{rel} is as shown in Fig.2.7 [2.3]. It has been selected to be compatible with the transmitting LED which radiates 635nm visible light. Such photodiode responses to 635nm light at 70% of the maximum sensitivity which occurs at 850nm (infrared). Ideally, for a single-wavelength system, it would require a photodiode that has a narrow bandwidth centred at carrier's wavelength in order to minimise high power interference appearing at other wavelengths. But that type of *high-Q*, single wavelength photodiode at 635nm is very expensive and it has not been opted for the low-cost design.

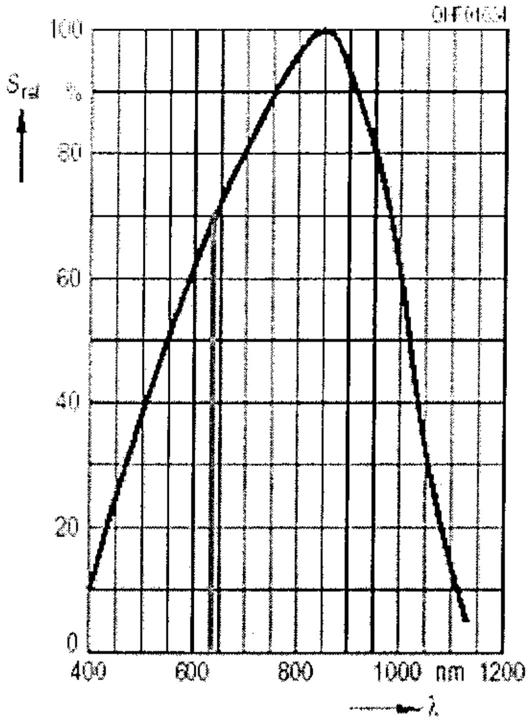


Fig.2.7: *Photodiode SFH2030 relative sensitivity as a function of wavelength*

Light receiving directionality of the photodiode is depicted in Fig.2.8 where it is found out that the half-angle is at 20^{O} where the relative sensitivity drops by 50%.

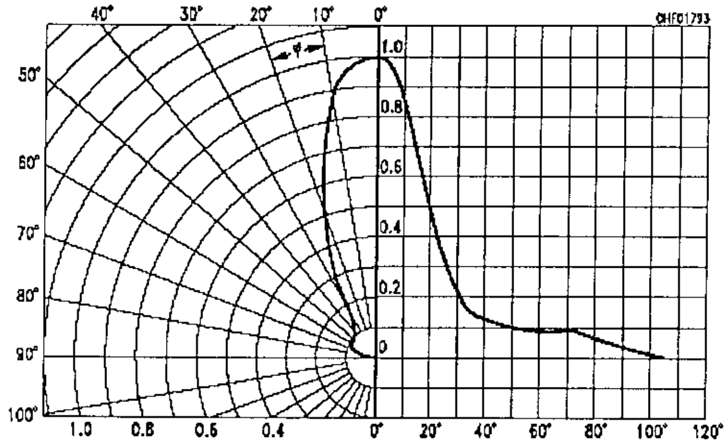


Fig.2.8: *Photodiode SFH203 directional characteristic*

2.5 Interface circuitries

Interface circuit provides signal conditioning and generating some specific signals in order to comply with IEEE 802.3 standard. It can be divided into two major parts: (a) circuit that interfaces with transmitter and (b) circuit that interface with receiver as shown in Fig.2.9.

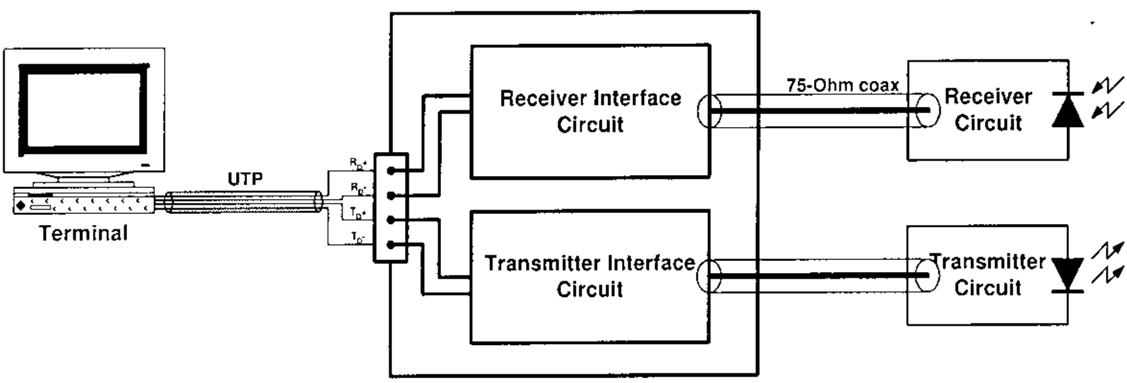


Fig.2.9: *Transceiver interface block diagram on one end of the FSO system*

Transmitter Interface Circuits

Transmitter interface circuit converts differential signals T_D+, T_D- from Ethernet card to a single signal and deliver to the transmitter. Moreover, it also generates 1MHz square wave while no data packet is being transmitted in order to comply with IEEE 802.3 standard. This signal will also be useful for the transceiver aiming during installation process.

Receiver Interface Circuits

Receiver interface circuit retrieves a single-end signal from the receiver and converts it to differential signal R_D+, R_D- for Ethernet card. While there is no data coming from the transmitter on the other, the transmitter interface circuit produces a specific pulse signal for the Ethernet card following IEEE 802.3 standard.

2.6 Summary

The FSO system has been reviewed to aid understanding of overall structure before going into detailed design and implementation in the subsequent chapters. Critical components, namely LED and photodiode, which play vital roles in determining system performances, are discussed and their properties are also given accordingly. It has been emphasised that the components selection and design methodologies are optimised to minimise the cost of the transceiver.

2.7 References

[2.1] S. Bloom, "The Physics of Free-Space Optics," Air Fiber white paper, available online at http://www.airfiber.com

[2.2] LUMILEDS, SuperFlux LEDS datasheet, HPWT-BD00-E4000.

[2.3] Siemens, SFH2030 photodiode datasheet.

Chapter 3 Transmitter Design

3.1 Introduction

The transmitter converts electrical information signal into light and emit energy containing data signal into free space. In order to achieve sufficient bandwidth of 10Mbps for the intended applications, the transmitter has to be designed so that it can provide high-speed switching current to drive the front-end LED. In this chapter, transmitter design techniques will be explained and clarified with simulation and experimental results.

3.2 Transmitter Building Blocks

The transmitter can be viewed as three main blocks: (1) a limiting amplifier (2) a current driver and (3) an LED. Data signal voltage coming from the interface circuit enters the transmitter at the input of the limiting amplifier where a signal is amplified and limited to a well-defined voltage level. This voltage signal is further fed into the current driver, which in turn converts the voltage signal into current signal before supplying to the LED.

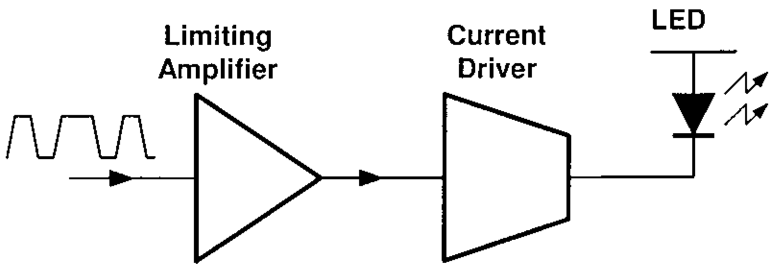


Fig.3.1: *FSO transmitter building block*

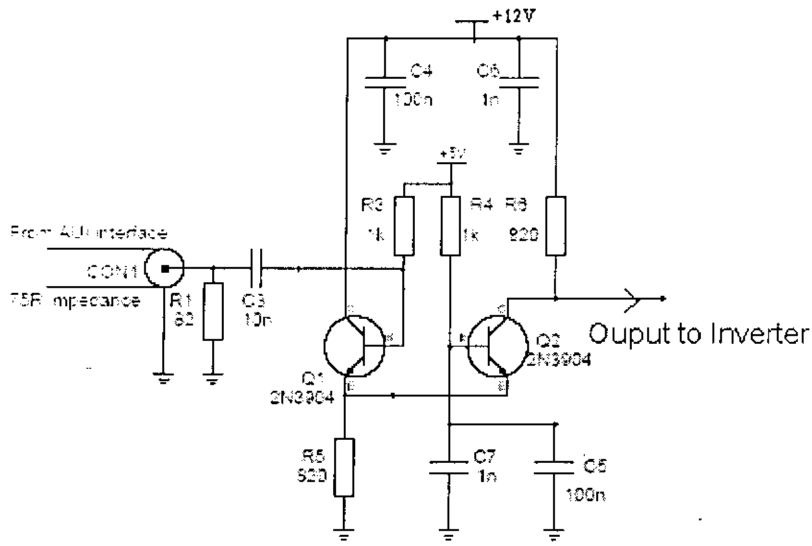


Fig.3.2: *Limiting amplifier*

3.3 Limiting Amplifier

The limiting amplifier is displayed in Fig.3.2 where two bipolar junction transistors, BJTs form an emitter-coupled pair as a main part of the amplifier. A widely available, low-cost discrete BJT 2N3904 is employed in real implementation. The data signal coming from the interface circuit via 75-Ω cable, where it is impedance matched at the input of the amplifier by a network comprising 82-Ω R1 and 1-kΩ R3 (considering C3 shorted at high frequency). C3 is mainly there to provide DC separation between interface and transmitter circuits. The BJTs are voltage biased at their bases via R3 and R4 at 5V which approximately sets a quiescent current of (5–0.7)/(2×820) = 2.6mA for each transistor. The output voltage is at the collector of Q2 connecting with resistive load of 820Ω. It thus renders a limiting peak-to-peak voltage swing of $820\times2\times2.6\times10^{-3}$ = 4.3V. This magnitude of voltage swing is chosen to be sufficient to switch a current driver. Note that this limiting amplifier operate under a large signal condition whose input is a large pulse coming from the interface circuit. The amplifier therefore may be seen behaving as a simple switch controlled by data signal pulse. However, in order to visualise how the amplifier perform in operating frequency merit, an AC (small-signal) simulation is carried out in PSPICE [3.1] as depicted in Fig.3.3.

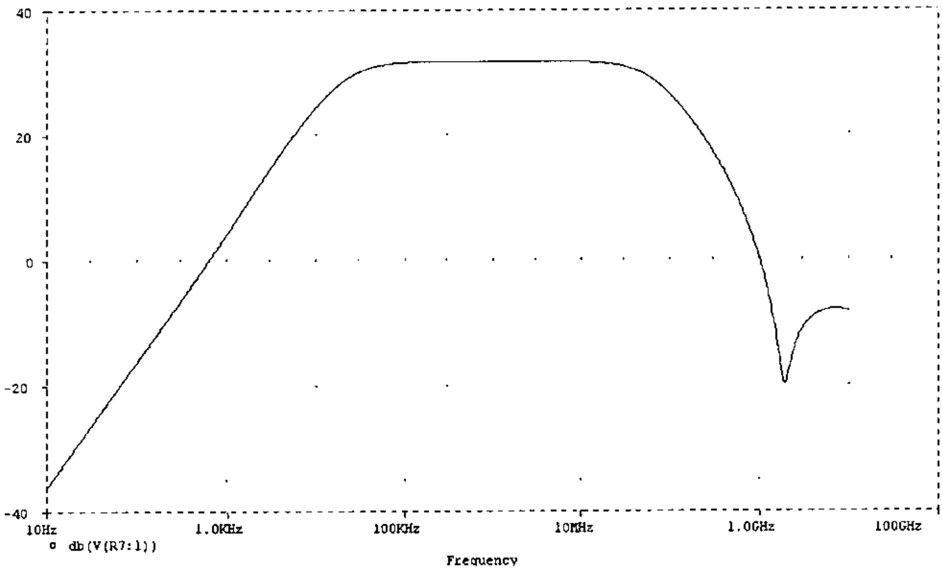


Fig.3.3: *Simulated AC response of the limiting amplifier*

It can be seen that bandwidth of the amplifier exceeds 10MHz specification of the intended FSO system. The 30-dB small signal gain suggests large amplification factor, although it is meaningless regarding a large signal operating condition. Time-domain analysis is also simulated as shown in Fig.3.4 with an input signal of a 10MHz 700mV$_{p-p}$ square wave. The output peak-to-peak swing is 3.96V$_{p-p}$ which is less than 8% from the predicted value. It is clear that because of the amplifier's limited bandwidth, the intended output square waveform is shaped. Measured result in time domain is shown in Fig.3.45 depicting the output signal which looks similar to the simulated one.

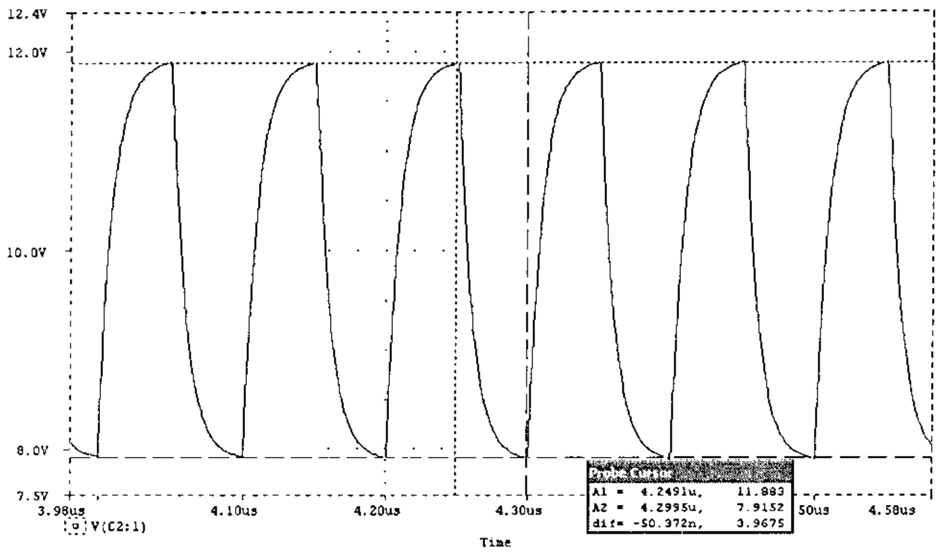


Fig.3.4: *Simulated limiting amplifier's output in time-domain*

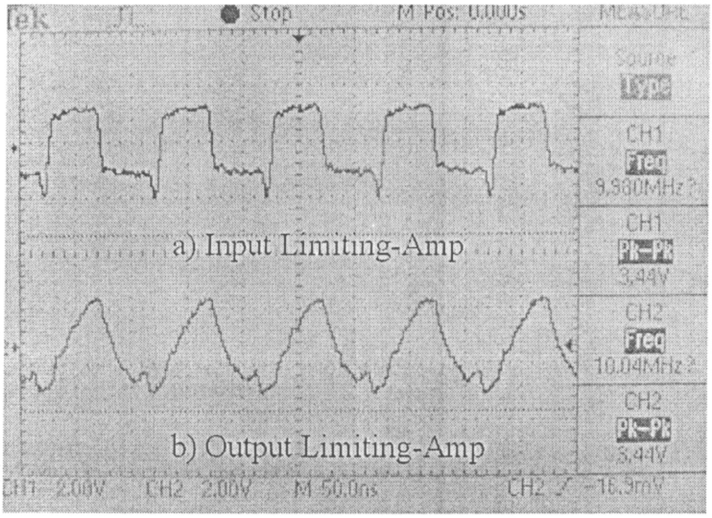


Fig.3.5: *Measured limiting amplifier's output time-domain*

3.4 Current Driver and LED

Voltage-to-current conversion can simply be accomplished by a resistor as demonstrated in Fig.3.6. The current driver consists of a two-stage inverter and an 8.2-Ω resistor. In practise, these inverters can be obtained from three 74HC04 integrated circuits which contain six inverters inside one package [3.2]. In simulation the LED can be modelled in the simplest form with 30-Ω resistor connecting in parallel with a parasitic capacitance of 40pF as described in the LED datasheet [3.3]. A more realistic modelling of the LED can also be done basing on its radiating power characteristic over forward current. Note that the first-stage inverter is biased at a fixed DC voltage in order to assist inverter switching.

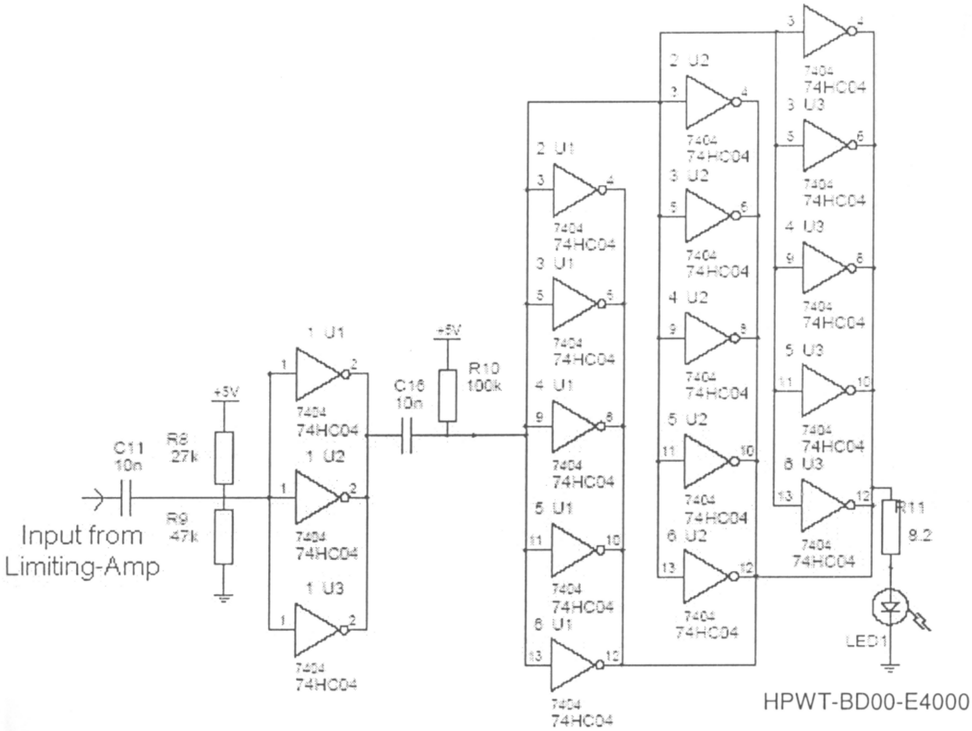


Fig.3.6: *Current driver and LED*

3.5 Complete transmitter and prototype implementation

Combining the limiting amplifier, the current driver and the LED renders a simplified complete transmitter circuit shown in Fig.3.7. The transmitter prototype is air-wired and soldered inside a metal case without using a PCB as photographed in Fig.3.8. The metal case provides large ground plane and effective shielding to minimise electromagnetic interference. Note that the transmitter obtains 12V from a single power supply and the 5V supply voltage (for transistor biasing and supplying the inverter ICs) is provided by a single 7805 regulator IC.

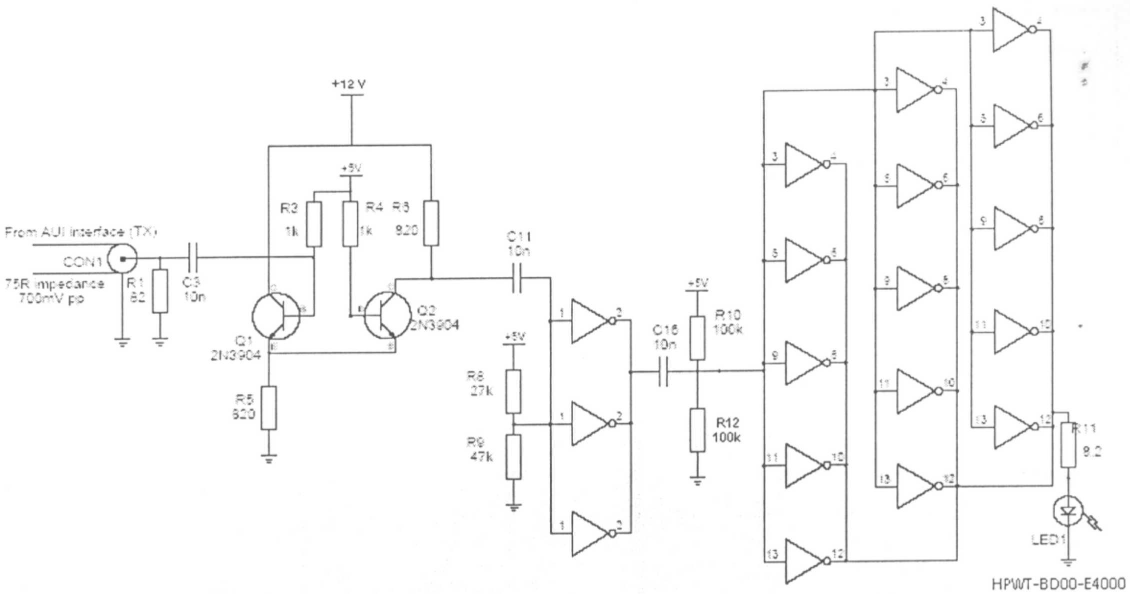


Fig.3.7: *Simplified complete transmitter schematic*

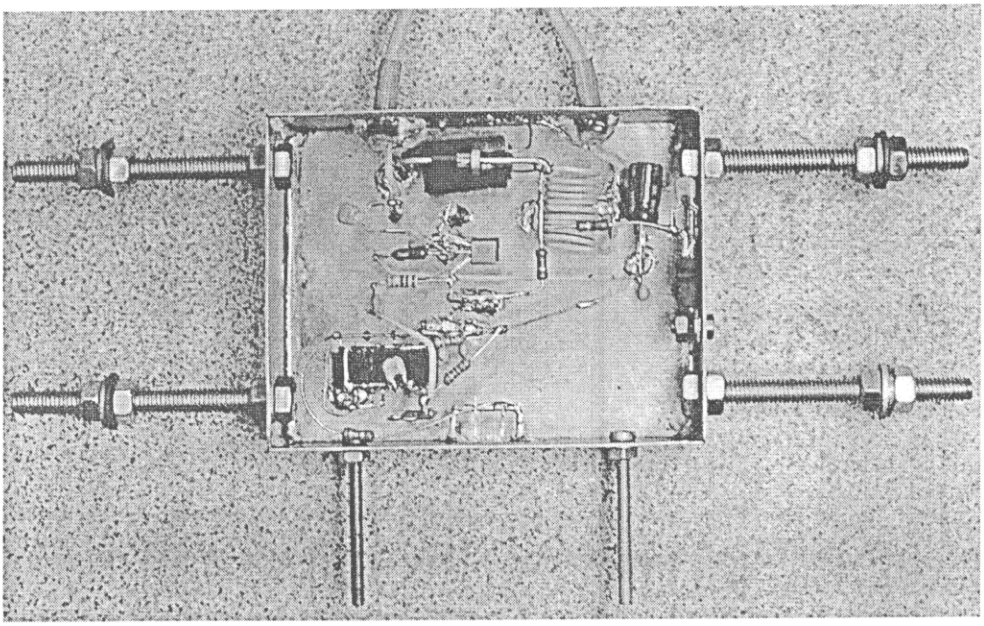
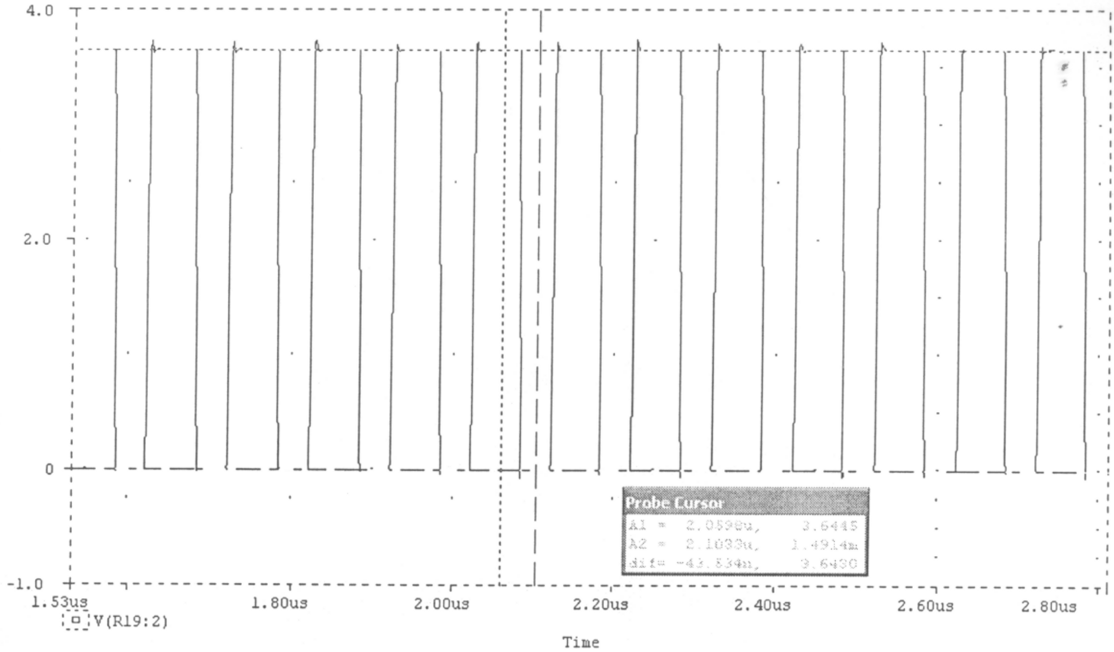
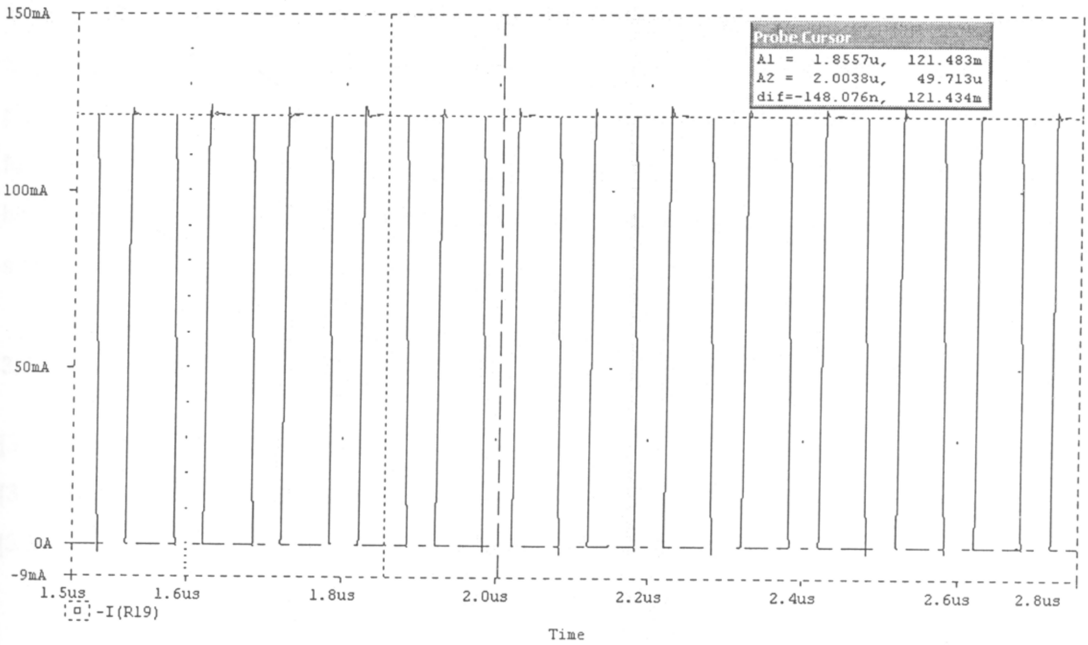


Fig.3.8: *Transmitter prototype implementation*

Illustrated in Fig.3.9 is a time-domain simulation result when subjecting the transmitter with 10MHz 700mV$_{p\text{-}p}$ square wave input signal. The output of the inverter shows a desired 10MHz square wave signal with magnitude of 3.64V$_{p\text{-}p}$ where the current magnitude flowing into the LED is 120mA$_{p\text{-}p}$ sufficient to make the LED radiate optical light with luminous intensity over 3 lm.



(a) Inverter's output



(b) LED's current

Fig.3.9: *Transmitter time-domain simulation*

The measured inverter's output waveform was found to be in a close agreement with simulated results (Fig.3.10). The output voltage magnitude is at 3.44$V_{p\text{-}p}$ which is just 5% below the simulated waveform. Ringing sign clearly seen in the waveform may be caused by lead and package inductance.

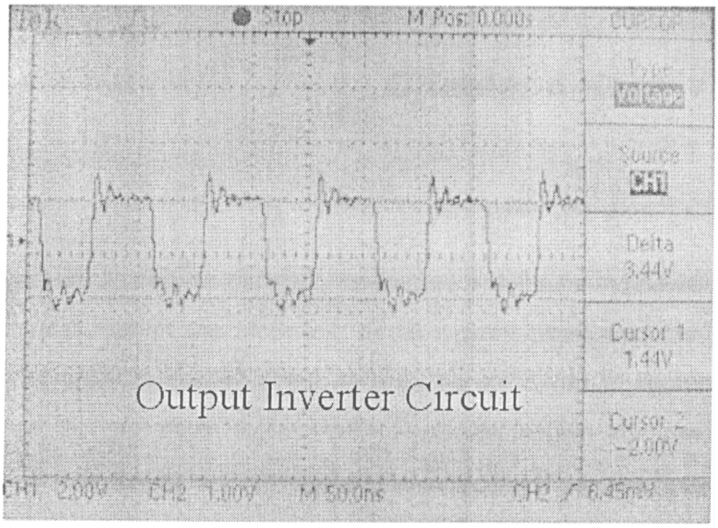


Fig.3.10: *Measured transmitter output voltage*

3.6 Summary

Transmitter design and implementation for the FSO transceiver has been described. Simulation and experimental results were also given to demonstrate feasibility to perform 10MHz electrical to optical signal conversion. In order to verify the functionalities of the transmitter to see whether it can successfully emit optical signal into free-space, it is required to have a detector, i.e. a receiver, to convert an optical signal back to an electrical signal as explained in the next chapter.

3.7 References

[3.1] Microsim, PSPICE Manual.

[3.2] HEX Inverter 74HC04 datasheet.

[3.3] LUMILEDS, SuperFlux LEDS datasheet, HPWT-BD00-E4000.

Chapter 4 Receiver Design

4.1 Introduction

In a wireless system, a receiver generally poses more difficulty in design compared to a transmitter, especially when the incoming signal is very weak and being at very high frequency. This chapter discusses circuit techniques employed to implement an optical receiver suitable for the FSO transceiver. It will be shown that with good circuit techniques being exercised, a high-performance receiver can be implemented from inexpensive electronic components.

4.2 Receiver Building Blocks

The receiver can be viewed as three separate building blocks as shown in Fig.4.1. An incoming optical data signal is converted into an electrical current by a photodiode. This current is further converted into a signal voltage by a transimpedance amplifier – a single resistor can effectively perform this task. However, the parasitic capacitance of the photodiode limits bandwidth of the receiver's front-end and it consequently shapes a data current signal into a triangular voltage waveform. Thus, in a later stage, a differentiator is needed to recover a square waveform from this triangular signal. A limiter is employed in the last stage of the receiver in order to further amplify the signal from the previous stage and limit a signal voltage to a particular level before delivering the signal to the interface circuit.

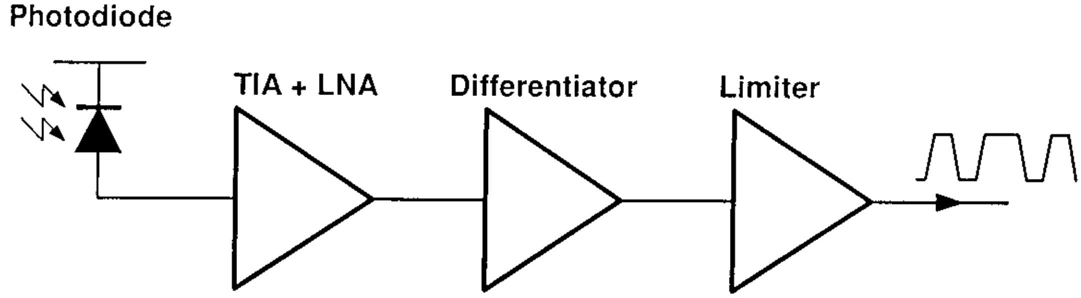


Fig.4.1: *FSO receiver building blocks*

4.3 Current-to-voltage conversion and low-noise amplification

The PiN Si photodiode SFH2030 from Siemens is employed to perform optical-to-electrical conversion. As depicted in Fig.4.2, a converted current signal is transformed into voltage signal by a single 100kΩ resistor. Measured result of optical-to-voltage signal conversion in Fig.4.3 was obtained by sending a 10-MHz square wave from the transmitter described in the previous chapter. It can be seen that the triangular wave is recovered instead of a square wave because of the photodiode's 11pF parasitic capacitance [4.1]. This bandwidth-limited behaviour could be described by current-to-voltage transfer function in *s* and $j\omega$ domain as follows

$$\frac{v_{out}}{i_{in}}(s) = \frac{R_{i2v}}{1+sRC_p}$$

$$\frac{v_{out}}{i_{in}}(j\omega) = \frac{R_{i2v}}{1+j\omega RC_p} \tag{4.1}$$

where C_p is an equivalent total capacitance connecting at the output to ground or supply voltage, R_{i2v} is a current-to-voltage conversion resistance. At low-frequency, i-v conversion gain is 100kΩ. This optical-electrical conversion can also be simulated by modelling a photodiode, in a simplest form, as a current source.

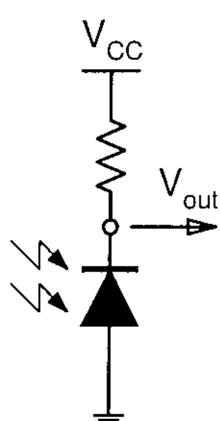


Fig.4.2: *Current-to-voltage conversion by a100kΩ resistor*

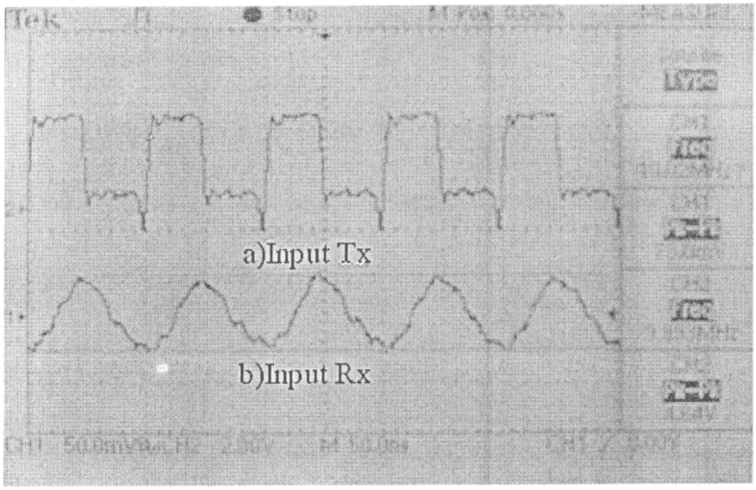


Fig.4.3: *Measured optical-to-voltage conversion by a100kΩ resistor*

The voltage output signal is further amplified by FET-based low-noise amplifier of Fig.4.4 in order to enhance voltage signal magnitude before being delivered to the differentiator. The BF998 or BF908 FETs can be used as the amplifier's active component. This dual-gate FET resembles two FET transistors connected in a cascade configuration which helps minimise Miller's capacitance effect and boost high-frequency performance. Voltage dc gain of this amplifier can be simply expressed by

$$\text{gain} = -g_m R_L \tag{4.2}$$

where g_m is the FET's transconductance and R_L is a load resistance = 560Ω. The g_m can be set by appropriately biasing the transistor according to the information given in the datasheet [4.2] as also shown in Fig.4.5 and Fig.4.6. In this particular, the design is set to obtain g_m ~ 24mS by making V_{G1S} = 0V and V_{G2S} = 4V with quiescent drain current of 10mA and provide a small-signal voltage dc gain of 22dB. In practice, the voltage at 10MHz is lower than this value because of the transistor's bandwidth limitation and parasitic capacitance.

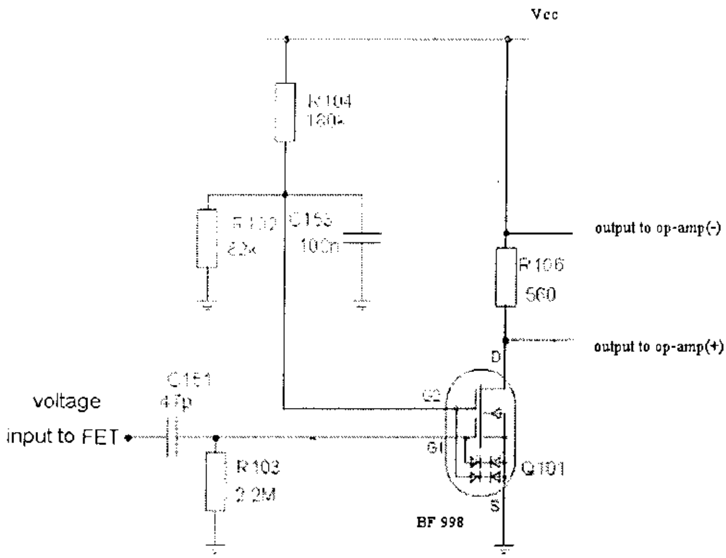


Fig.4.4: *Dual-gate FET-based low-noise amplifier*

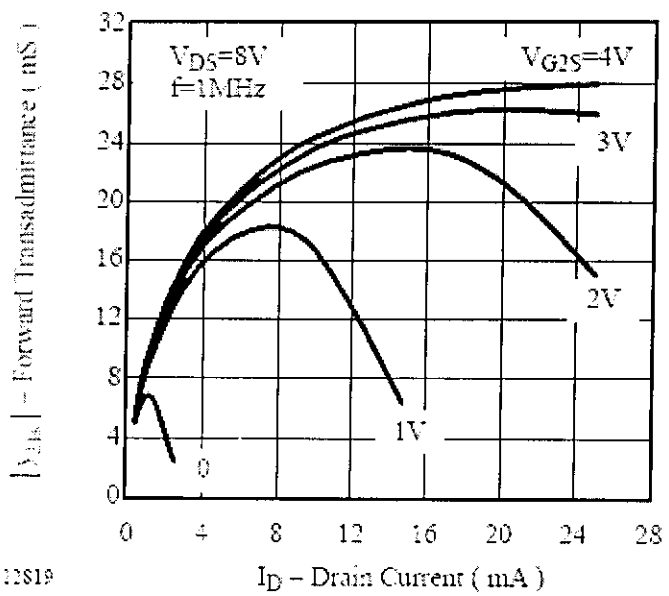


Fig.4.5: *FET transistor's transconductance characteristic*

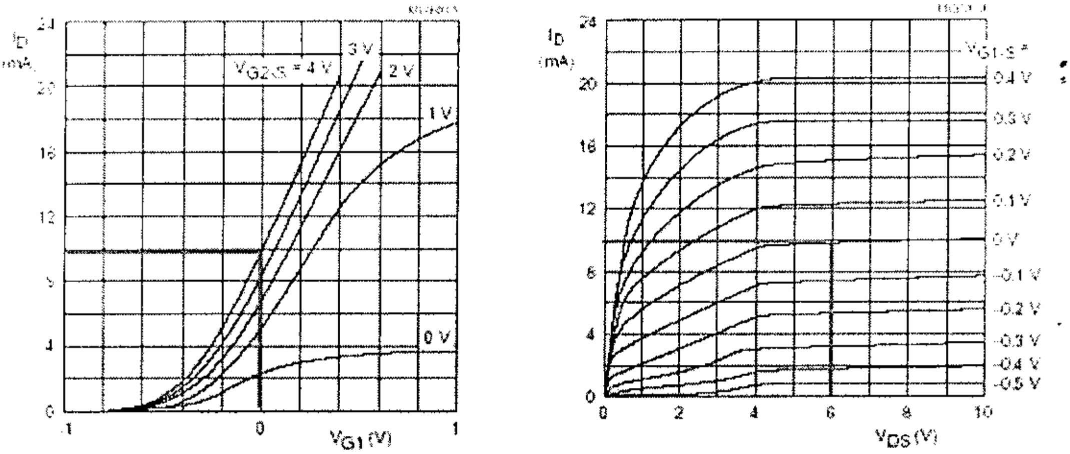


Fig.4.6: *FET transistor's I-V characteristic*

Simulation result by PSPICE in frequency domain is shown in Fig.4.7 indicating that at 10MHz a small-signal voltage gain is at 6.25 or 15.9dB. This magnitude of amplification is confirmed by measurement shown in Fig.4.8 suggesting a gain of 6.4 or 16.1dB – not very far from the simulated value.

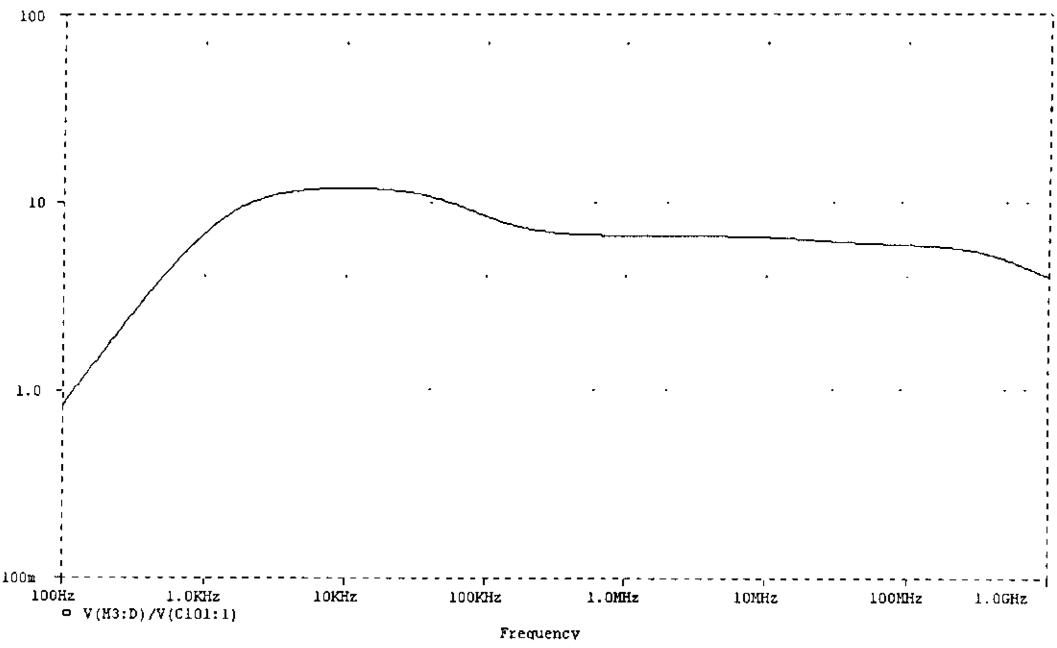
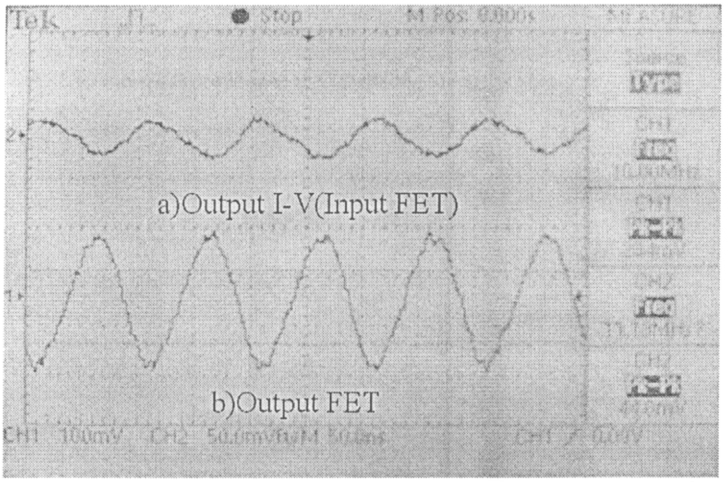


Fig.4.7: *Simulated low-noise amplifier frequency response*



Amplifier's signal at (a) input (b) output

Fig.4.8: *Measured low-noise amplifier time-domain response*

4.4 Differentiator

It is evident from the last section that a data pulse from the transmitter has been bandwidth limited and shaped into a triangular waveform by the receiver front-end. It thus need to differentiate this triangular signal so that the original data square wave can be fully recovered. A voltage differentiator circuit employed in the FSO receiver is as shown in Fig.4.9. The circuit utilised a dual-feedback video amplifier NE592 IC as the core component cooperating with 270pF capacitor to provide differentiation where its transfer function can be realised as [4.3]

$$\frac{V_{out}}{V_{in}} \approx \frac{1.4 \times 10^4}{Z(s)} \tag{4.3}$$

where Z(s) is an impedance between pin 4 and pin 11 of NE592. In this particular design, capacitor, C is employed to realised differentiation, that is

$$\frac{V_{out}}{V_{in}} \approx 1.4 \times 10^4 \times sC \tag{4.4}$$

with C = 270pF, the differentiator transfer function can be expressed in $j\omega$ domain as $j\omega \times 37.8 \times 10^{-6}$.

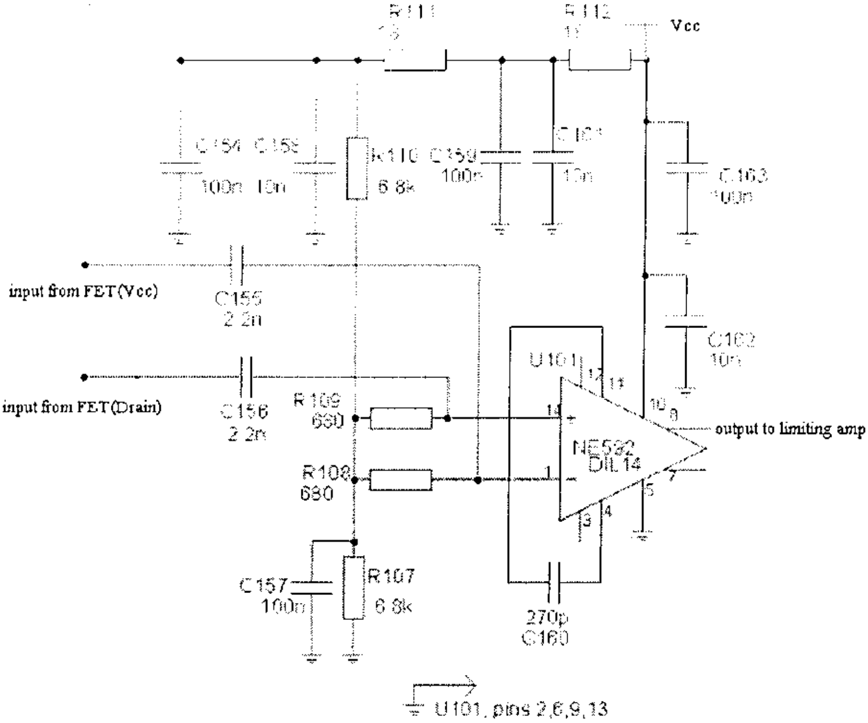


Fig.4.9: *Voltage differentiator*

Simulate frequency response of the differentiator is as pictured in Fig.4.10. Note that the NE592 model is not available in PSPICE; therefore it has to be modelled manually as shown in Fig.4.11 by using the detailed schematic available from a similar type of IC, i.e., uA733 [4.4]. The simulated result renders a desired differentiating function as well as amplification.

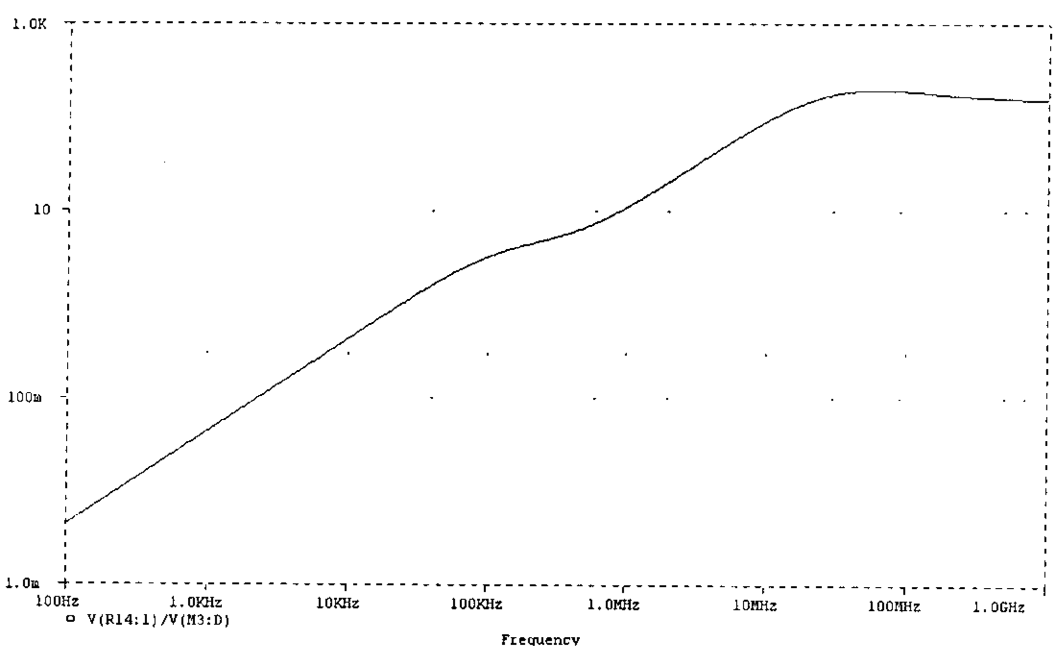


Fig.4.10: *Differentiator's frequency response*

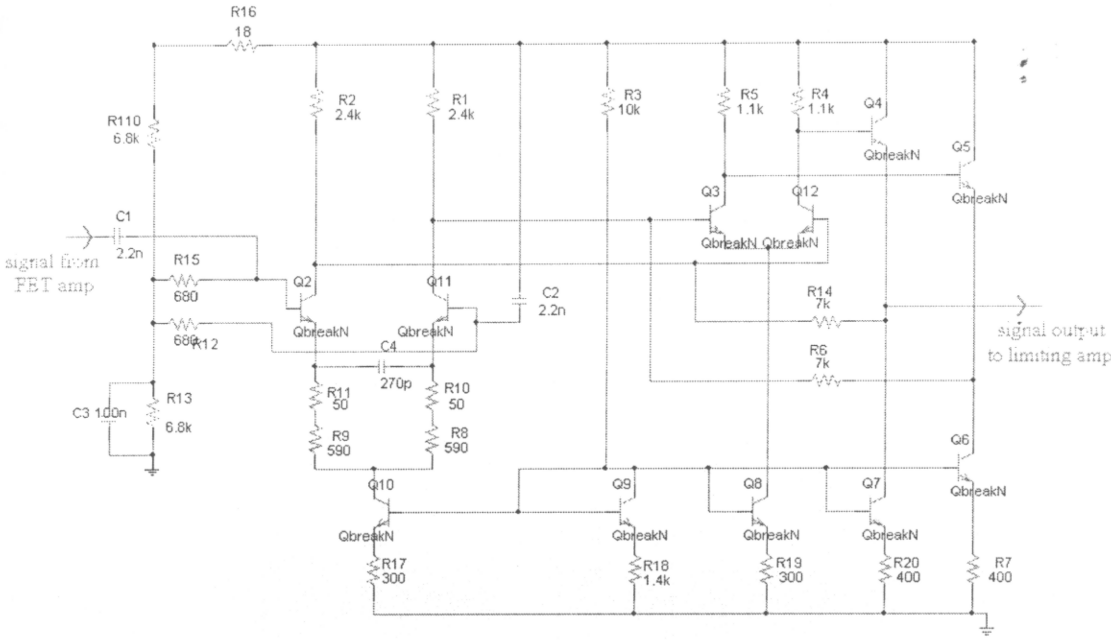


Fig.4.11: *NE592 is modelled by basing on uA733 schematic*

Measured results in Fig.4.12 indicate that the data pulse has been partly recovered from a triangular signal. The non-perfect square wave is not a problematic because such signal will be passed on to the later stage to be further amplified and level limited.

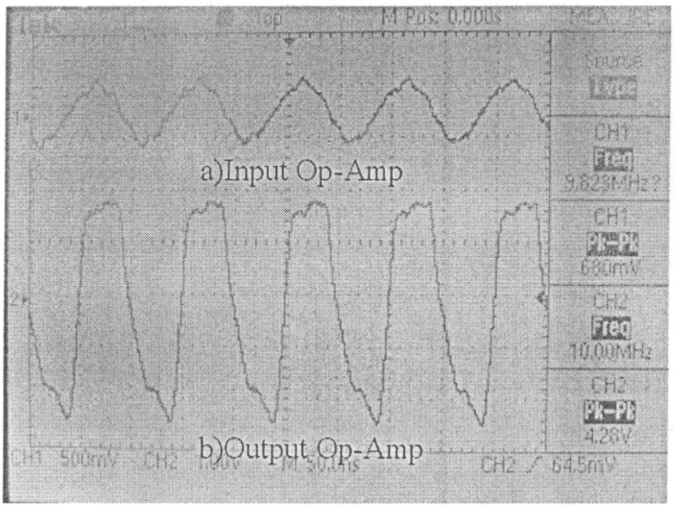


Fig.4.12: *Measurement at input (a) and output (b) of the differentiator*

4.5 Limiting Amplifier

A limiting amplifier receives signal from the differentiator and perform amplification as well as limit the output swing level. Moreover, this particular last stage has to provide impedance matching via 75-Ω cable to minimise reflection when the signal is delivered to the interface circuit. Shown in Fig.4.13 is a limiting amplifier based on emitter-couple pair. This kind of amplifier has been employed in the transmitter circuit as explained in previous chapter. The resistive output load is selected to be 75 Ω to provide a necessary matching. The output peak-to-peak voltage swing can be calculated to be $75*(6-0.7)/270 = 1.47V_{p-p}$.

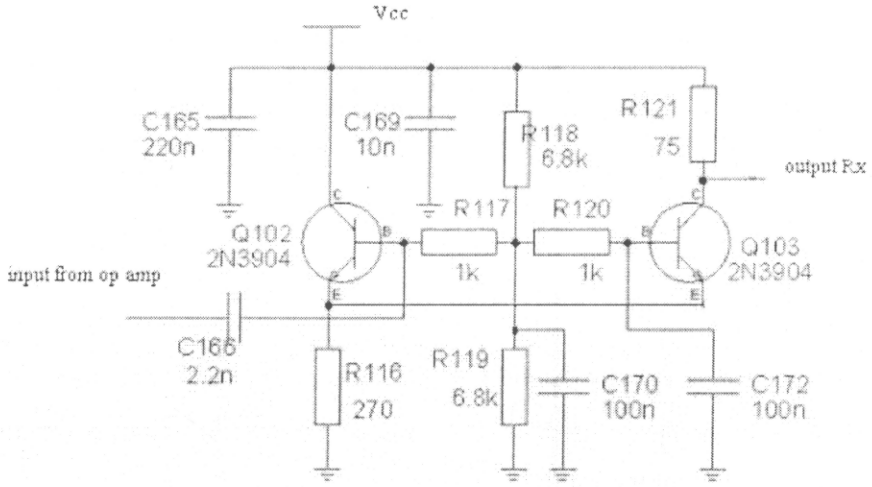


Fig.4.13: *Limiting amplifier for FSO receiver*

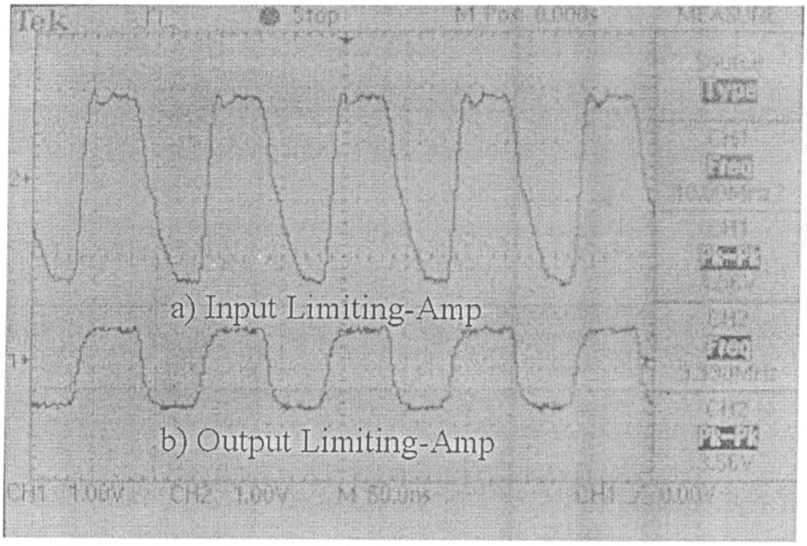


Fig.4.14: *Measured limiting amplifier's input output voltages*

Measured waveforms are displayed in Fig.4.14 comparing input and output signals which clearly suggests that the output has become more symmetrical and appropriate as data pulses for further signal processing by the interface circuitries. The peak-to-peak voltage swing is $1.56V_{p-p}$ which is slightly higher than predicted by the calculation.

4.6 Complete receiver and prototype implementation

Combination of the aforementioned circuitries results in a single receiver circuit depicting in Fig.4.15 as a simplified version. Prototype construction (Fig.4.16) has been done similarly to the transmitter, i.e. with air wiring and soldering and employing metal case as large ground plane and shielding. Note that shielding by metal sheet wall between three stages of the receiver has been exercised to reduce interference. The measured signal waveforms are illustrated in Fig.4.17 comparing the signal at the input of the transmitter with the output of the receiver. It can be seen that the transmitted signal can now be fully recovered and ready for further signal processing.

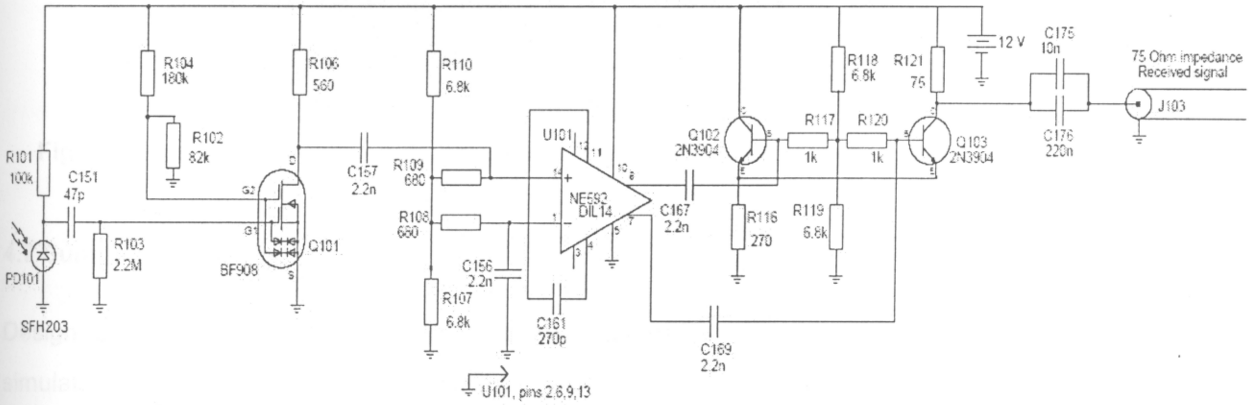


Fig.4.15: *Simplified complete receiver schematic*

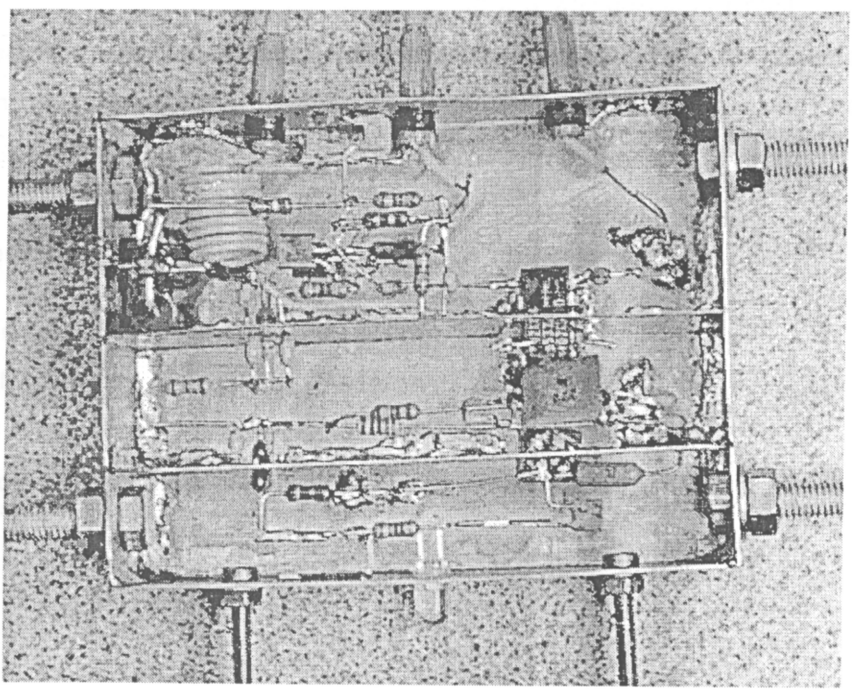


Fig.4.16: *Receiver prototype implementation*

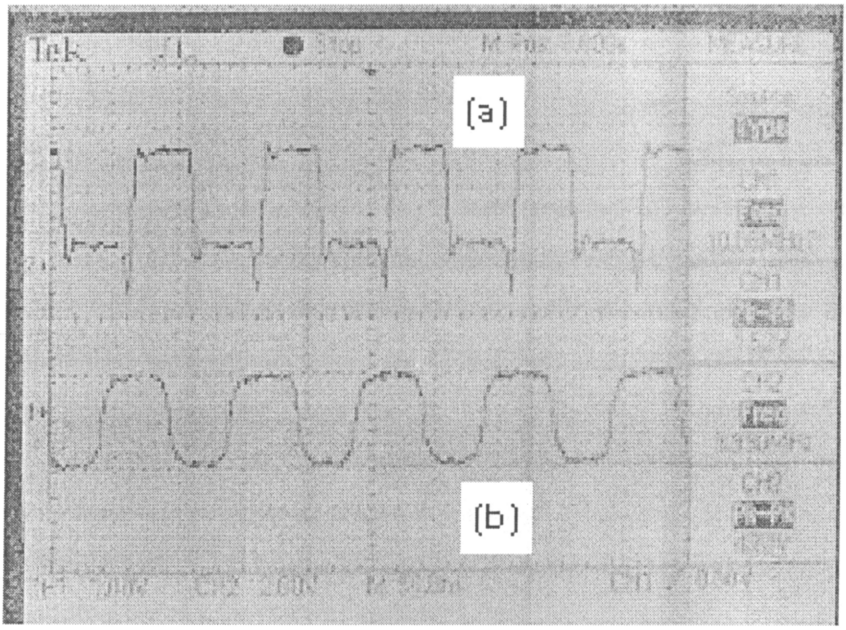


Fig.4.17: *Measured receiver output voltage(b) compared with transmitted signal (a)*

4.7 Summary

Design of receiver circuit for FSO transceiver has been addressed with presented simulated and measured results. Despite of a limited bandwidth of the cheap photodiode caused by its parasitic capacitance, it has been demonstrated that a good degree of signal recovery can be accomplished if a well-designed circuit technique is employed. The following chapters discuss design of the interface circuitries and how they can be integrated with the already designed transmitter and receiver to complete an FSO system.

4.8 References

[4.1] Siemens, photodiode datasheet, SFH2030.

[4.2] Philips, MOSFET datasheet, BF998.

[4.3] ON Semiconductor, Video amplifier datasheet, NE592.

[4.4] Texas Instrument, Differential video amplifier, uA733.

Chapter 5 Interface Circuit

5.1 Introduction

Interface circuitries establish themselves as key components in FSO systems where they allow the transmitter and receiver to communicate seamlessly with Ethernet card on computer workstation, switch, hub, and etc. In this preliminary research, the initial aim is to be able to link two personal computers by communications via PC's Ethernet or LAN. Interface circuit provides signal conditioning and generating some specific signals in order to comply with IEEE 802.3 standard. It can be divided into two major parts: (a) circuit that interfaces with transmitter and (b) circuit that interface with receiver as shown in Fig.5.1.

5.2 Interface building blocks for the transmitter

Transmitter interface circuit converts differential signals T_D+, T_D- from Ethernet card via an unshielded twist pair cable (UTP) to a single signal and send to the transmitter by employing DS26LS32 chip. Moreover, it also generates 1MHz square wave while no data packet is being transmitted as required by IEEE 802.3 standard. This signal will also be useful for the transceiver aiming during installation process.

On the other hand, receiver interface circuit retrieves a single-end signal from the receiver and converts it to differential signal R_D+, R_D- before delivering to Ethernet card using. While there is no data coming from the transmitter on the other side of the link, the transmitter interface circuit produces a specific pulse signal for the Ethernet card following IEEE 802.3 standard.

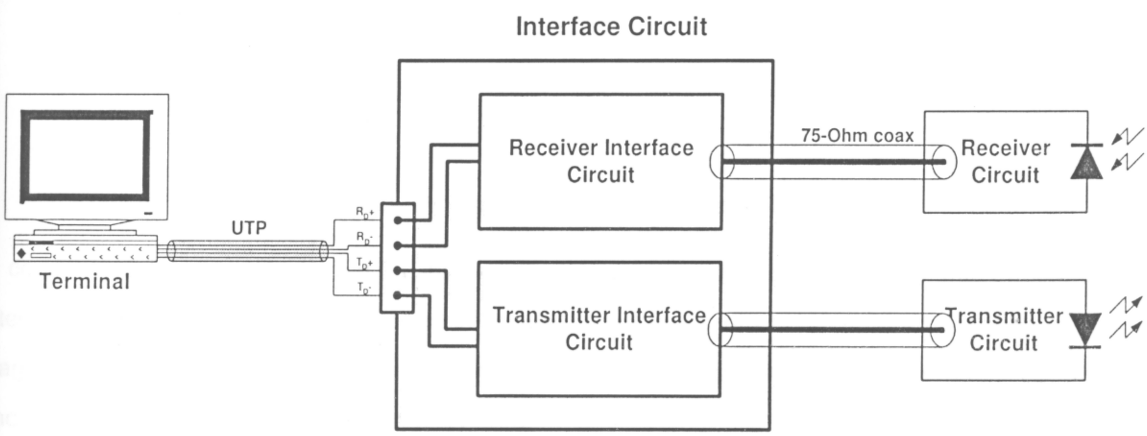


Fig.5.1: *FSO transceiver integration with interface circuits*

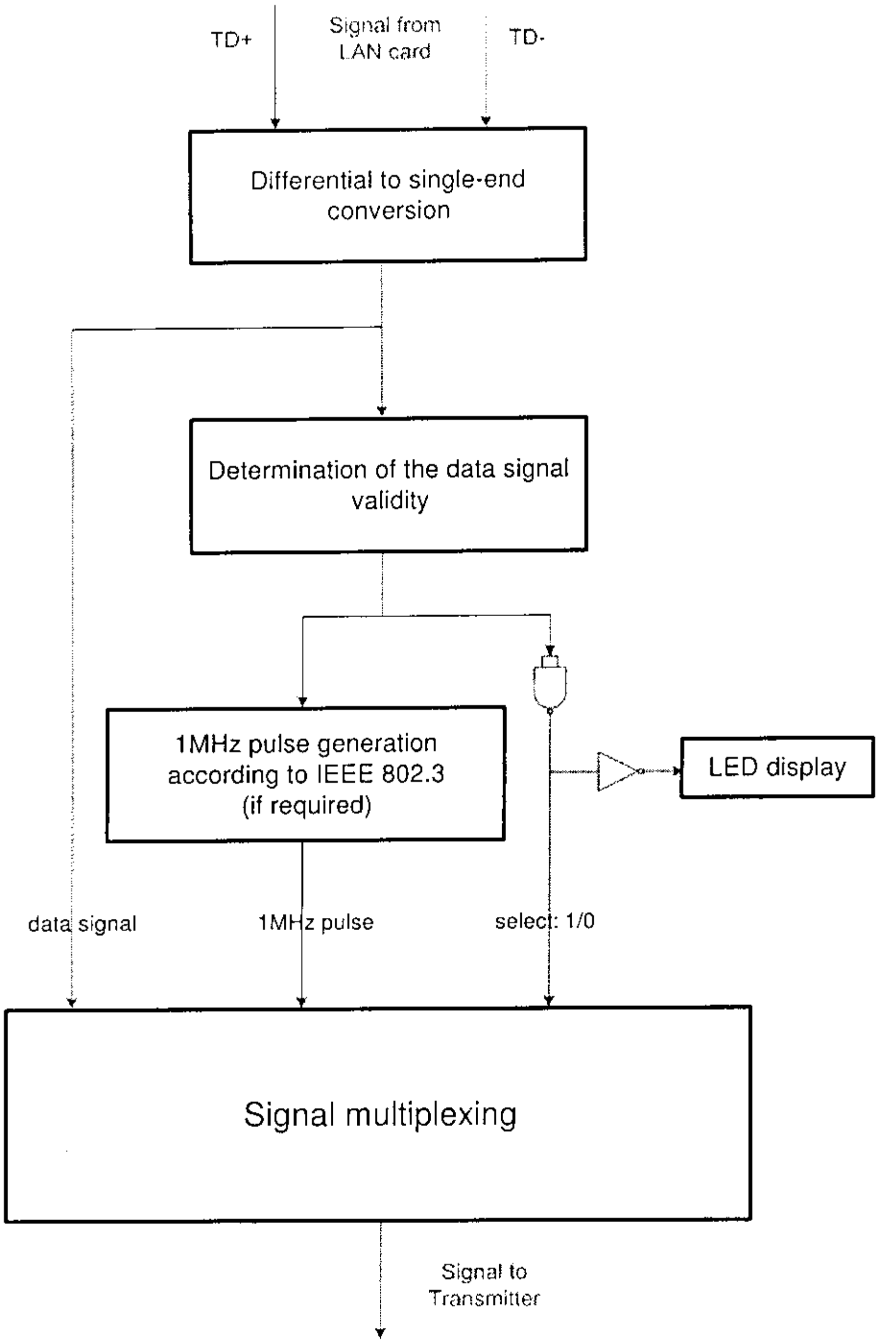


Fig.5.2: *Transmitter interface functionality*

A conceptual functionality in Fig.5.2 summarises the operations performed by the transmitter interface circuit. Such conceptual operations are transformed into building-block functional flow diagrams as shown Fig.5.3 and Fig.5.4 which signify two conditions of the operation, i.e. with and without data signal coming from LAN card.

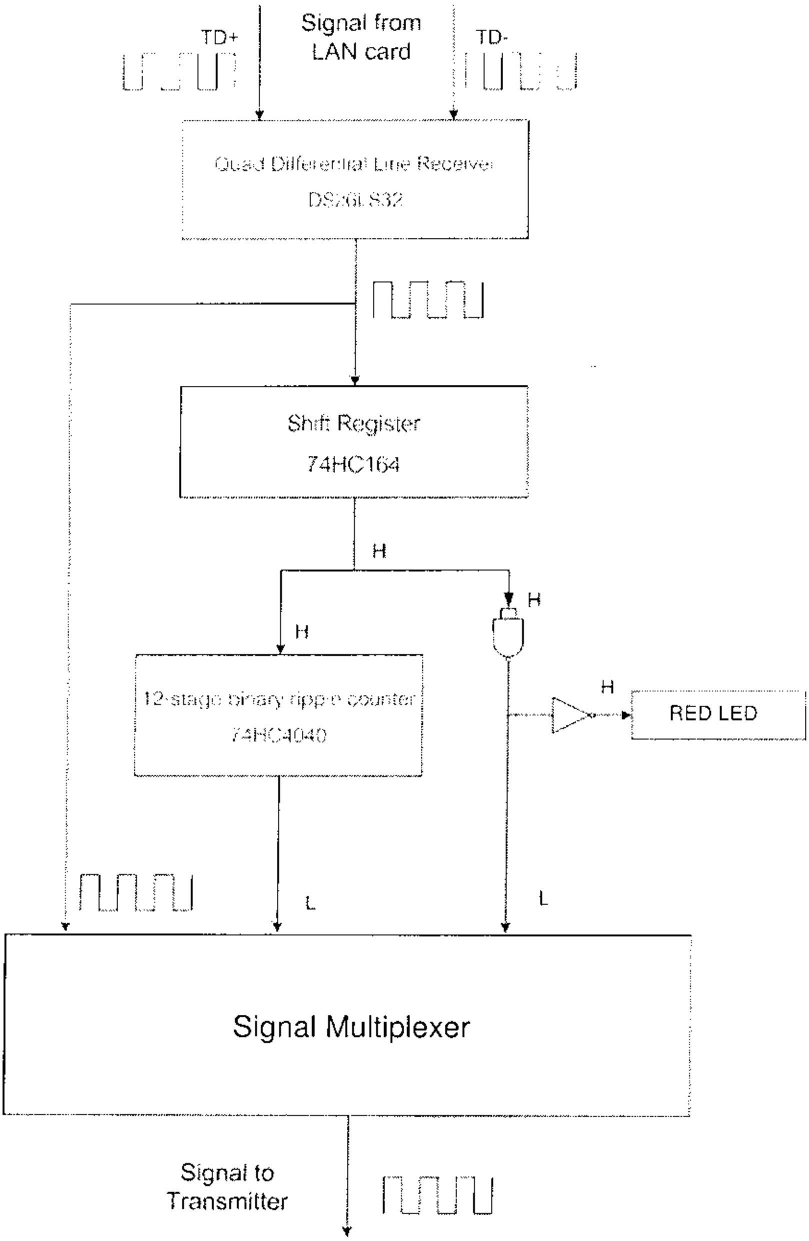


Fig.5.3: *Conceptual operational flow diagram of the transmitter interface circuit when there is signal from LAN card*

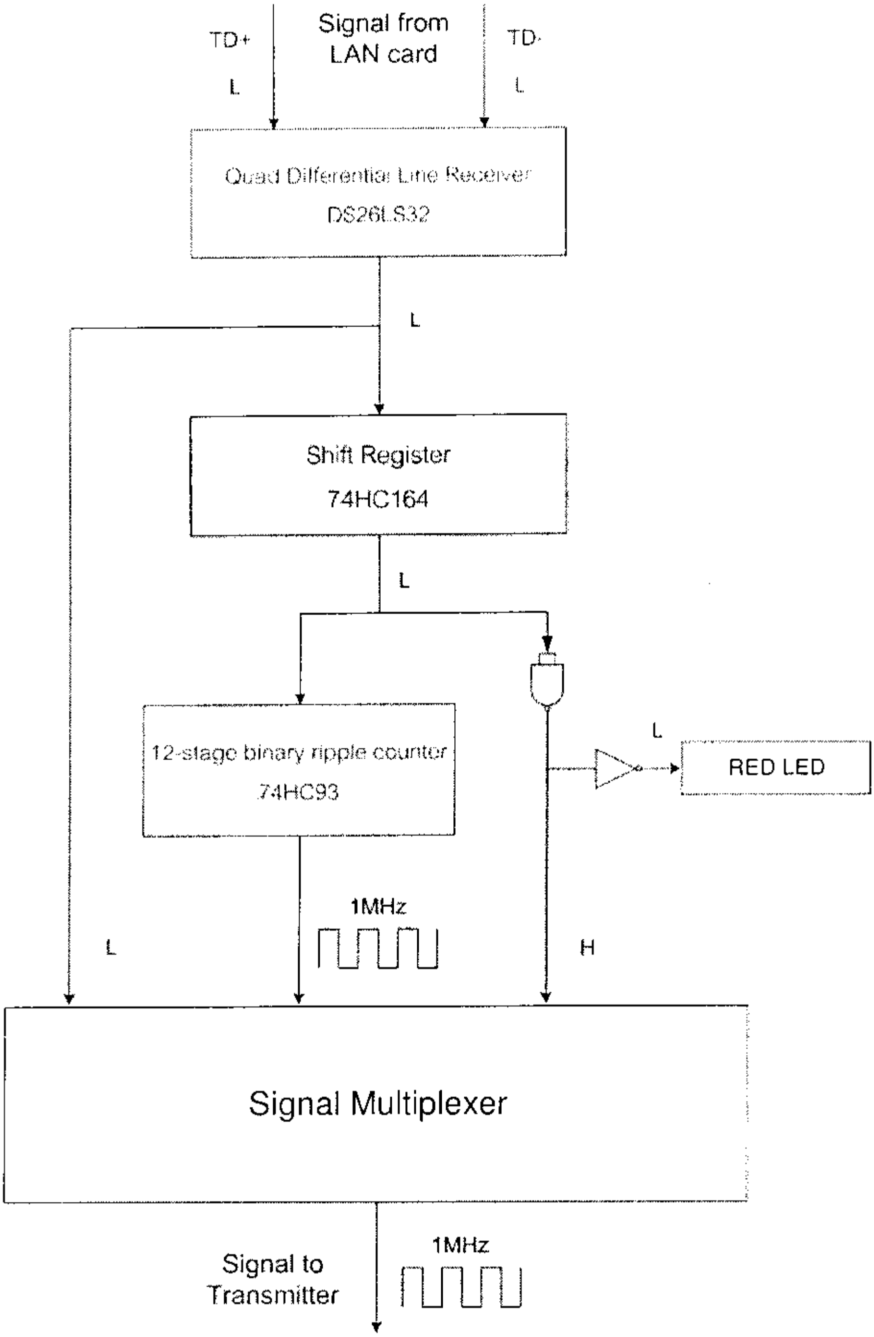


Fig.5.4: *Conceptual functional building blocks of the transmitter interface circuit when there is no signal from LAN card*

5.3 Transmitter interface circuit implementation

The first essential block of the transmitter interface circuitries is the quad differential line receiver DS26LS32 [5.1] which is employed to convert differential TD+ and TD- signal into a single-end before sending it to the transmitter as depicted in Fig.5.5.

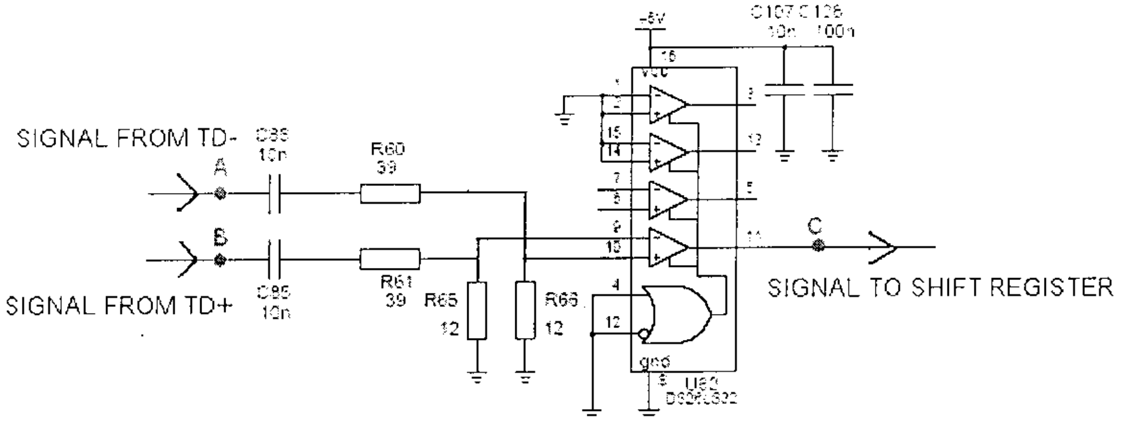


Fig.5.5: *Connection of the quad differential line receiver for differential-to-single-end conversion*

A digital logic circuitry in Fig.5.6 utilising three shift registers 74HC164 [5.2] is employed to determine the presence of the signal from LAN card by checking the signal coming from point C of the quad differential line receiver IC in Fig.5.5. When there is signal from the LAN card the logic at point B is high to disable a 1MHz clock generator and enable an already converted single-end data signal from the circuit in Fig.5.5 to be transmitted. Note that this digital circuit is synchronised by 16MHz clock signal.

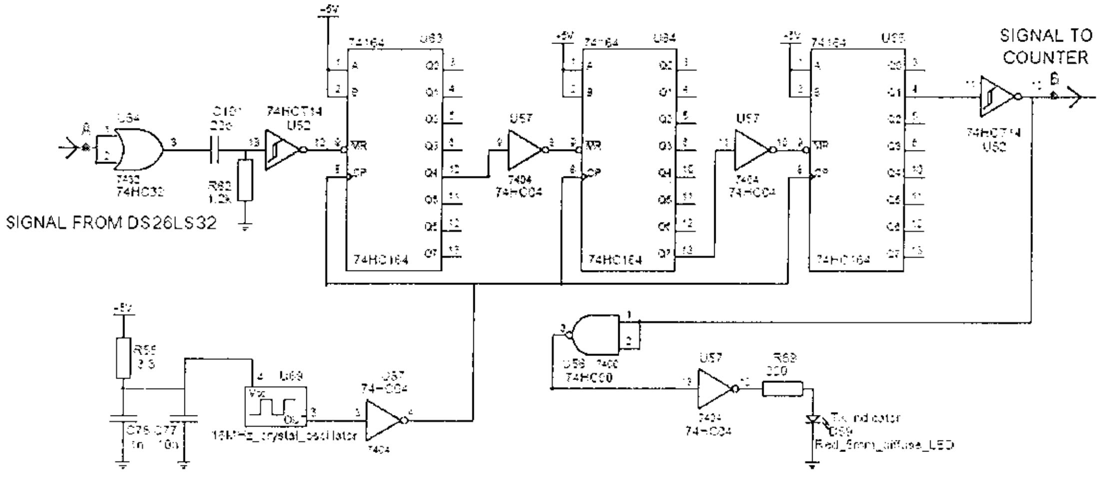


Fig.5.6: *Shift registers are employed to determine the presence of transmitted signal*

To comply with IEEE 802.3, 1MHz pulse signal has to be transmitted over optical link when there is an absence of data signal from Ethernet card. Such signal can be simply generated by a counter IC 74HC93 [5.3] as shown in Fig.5.7 by using 16MHz clock signal as an input.

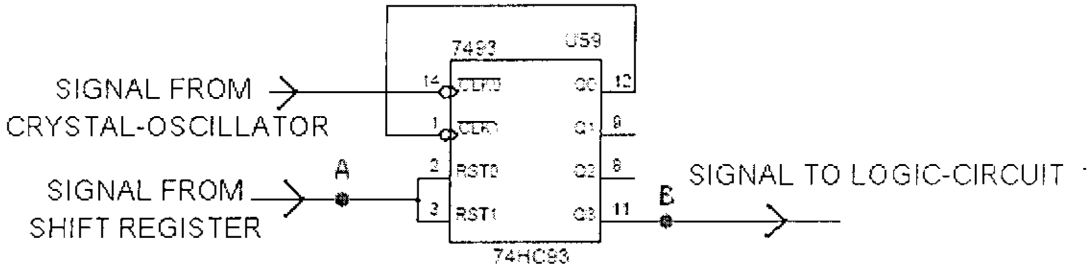


Fig.5.7: *74HC93 is employed to generate 1MHz signal*

Lastly, a multiplexer is required to route either a data signal or 1MHz signal with presence or absence of data signal. It can be simply designed with logic gates as depicted in Fig.5.8

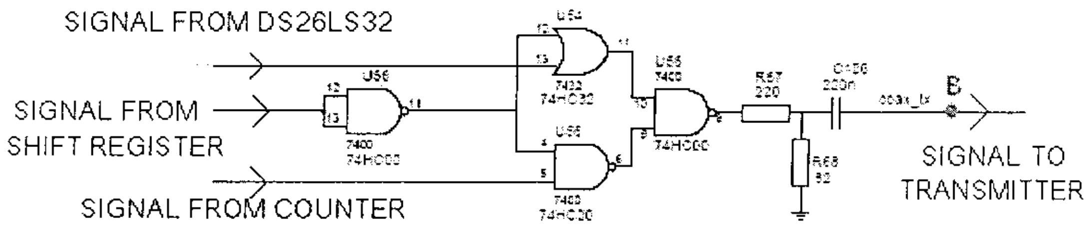


Fig.5.8: *Transmitter multiplexer implemented from logic gates*

Integrating all the above circuitries renders a complete transmitter interface circuit as schematically drawn in Fig.5.9. Measured the transmitter interface output signals are shown in Fig.5.10 comparing two conditions with and without data signal from Ethernet card. It demonstrated that the interface performed according its intended functionality. Note that signal distortion has been clearly observed for 10MHz signal and its main cause might be from the parasitic inductance.

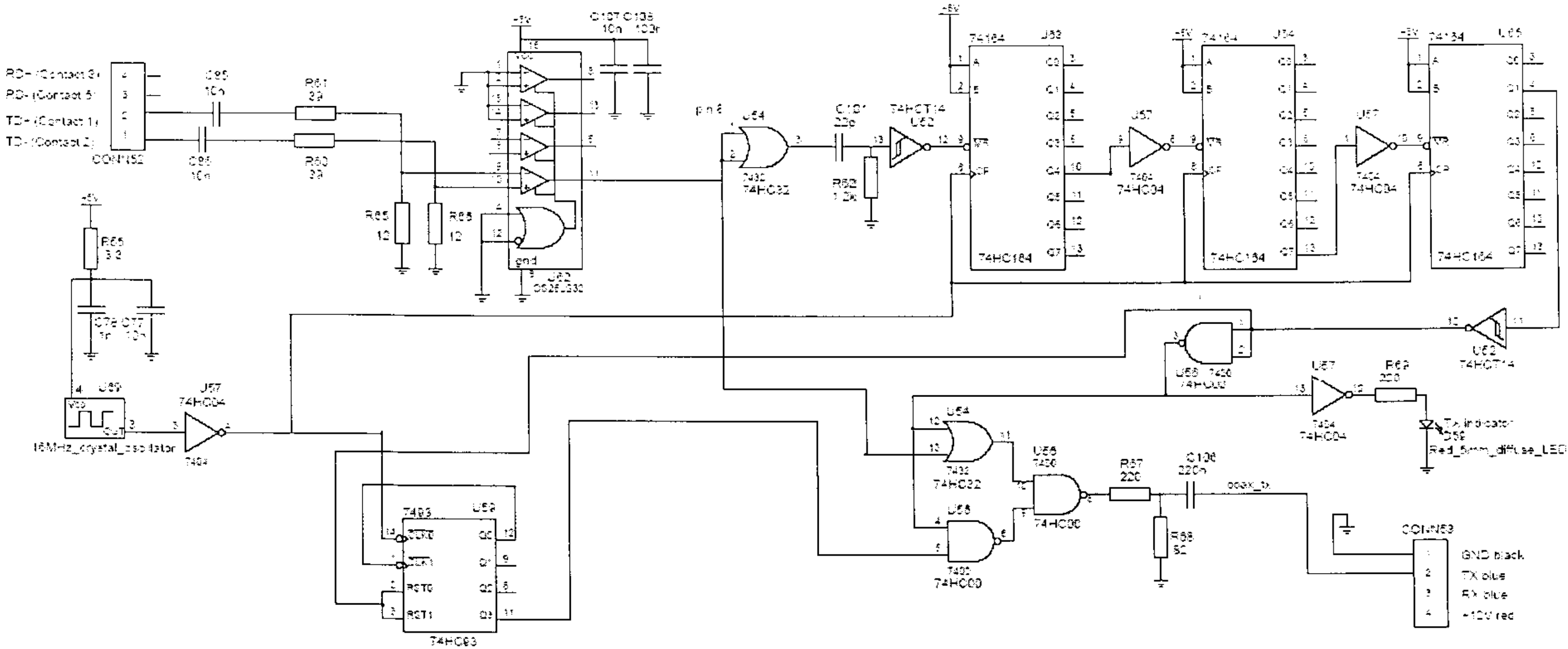
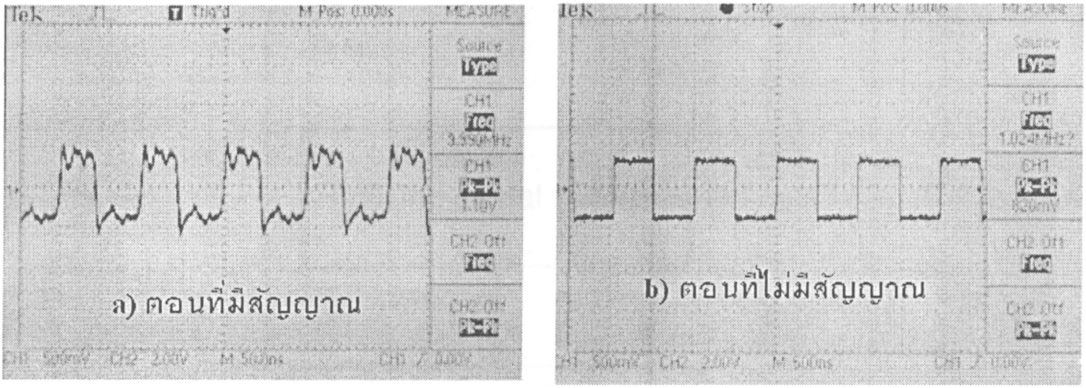


Fig.5.9: *Simplified complete schematic of the transmitter interface*



(a) With data signal (b) Without data signal

Fig.5.10: *Measured signals at the transmitter interface output (note change on time scale)*

5.4 Interface building blocks for the receiver

Conceptual functionality of the receiver interface is illustrated in Fig.5.11 where it performs a similar role but in a reverse direction to that of the transmitter interface. When the 10MHz data signal is available, it will be converted into a differential sign R_{D+} and R_{D-} and sent to Ethernet card via UTP cable. In the absence of 10MHz data signal, there would be a 1MHz pulse coming in from the other side of FSO link. This 1MHz pulse is also detected and enables a logic circuitry to generate pulse trains sent to an Ethernet card as part of IEEE 802.3 standard, simply to identify that there is no data coming but the link is still active. The corresponding building-block functional flow diagrams are as shown Fig.5.12 and Fig.5.13 which distinguish two conditions of the operation, i.e. with and without data signal coming from the other side of communication link.

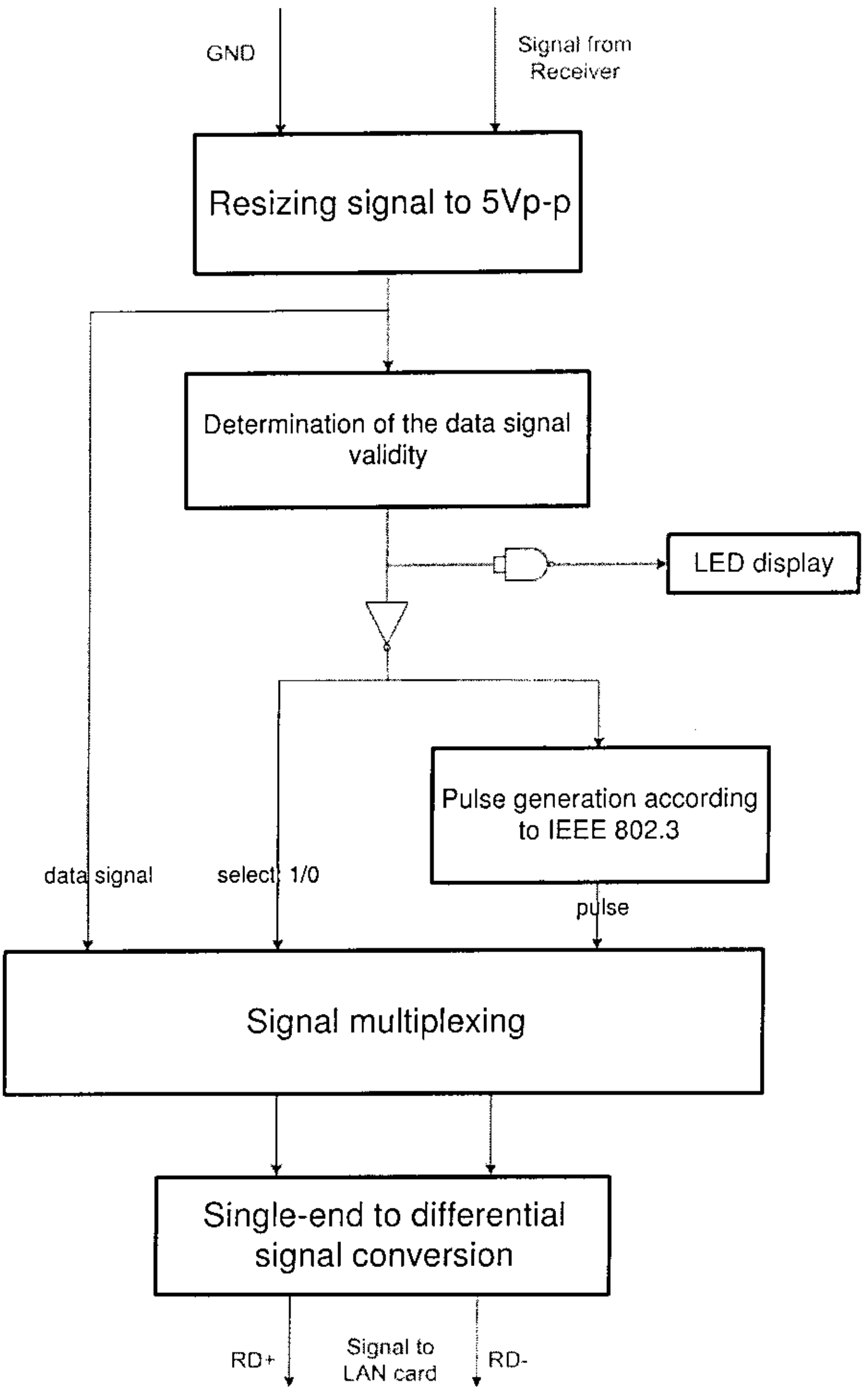


Fig.5.11: *Receiver interface functionality*

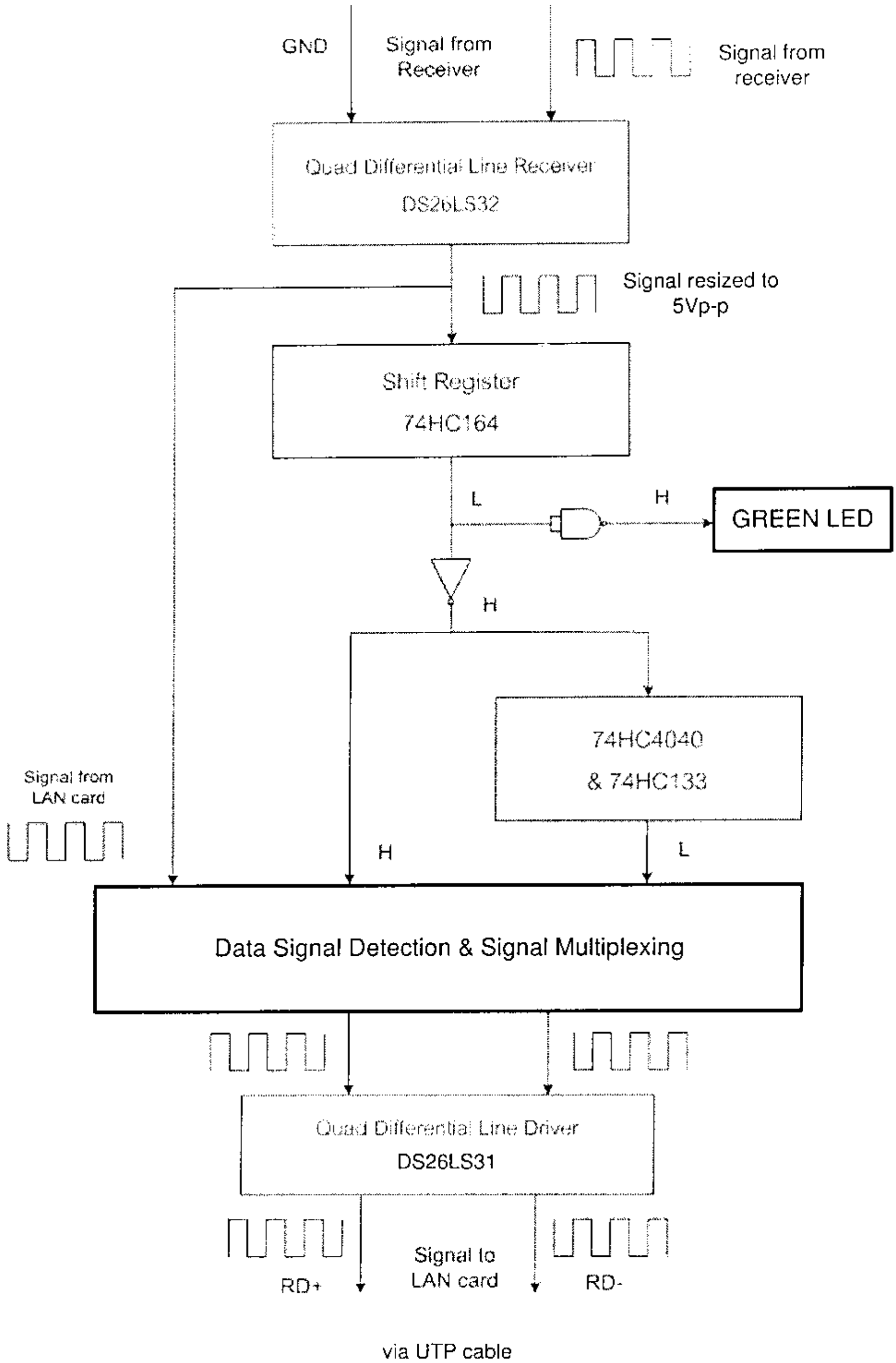


Fig.5.12: *Conceptual operational flow diagram of the receiver interface circuit with data signal*

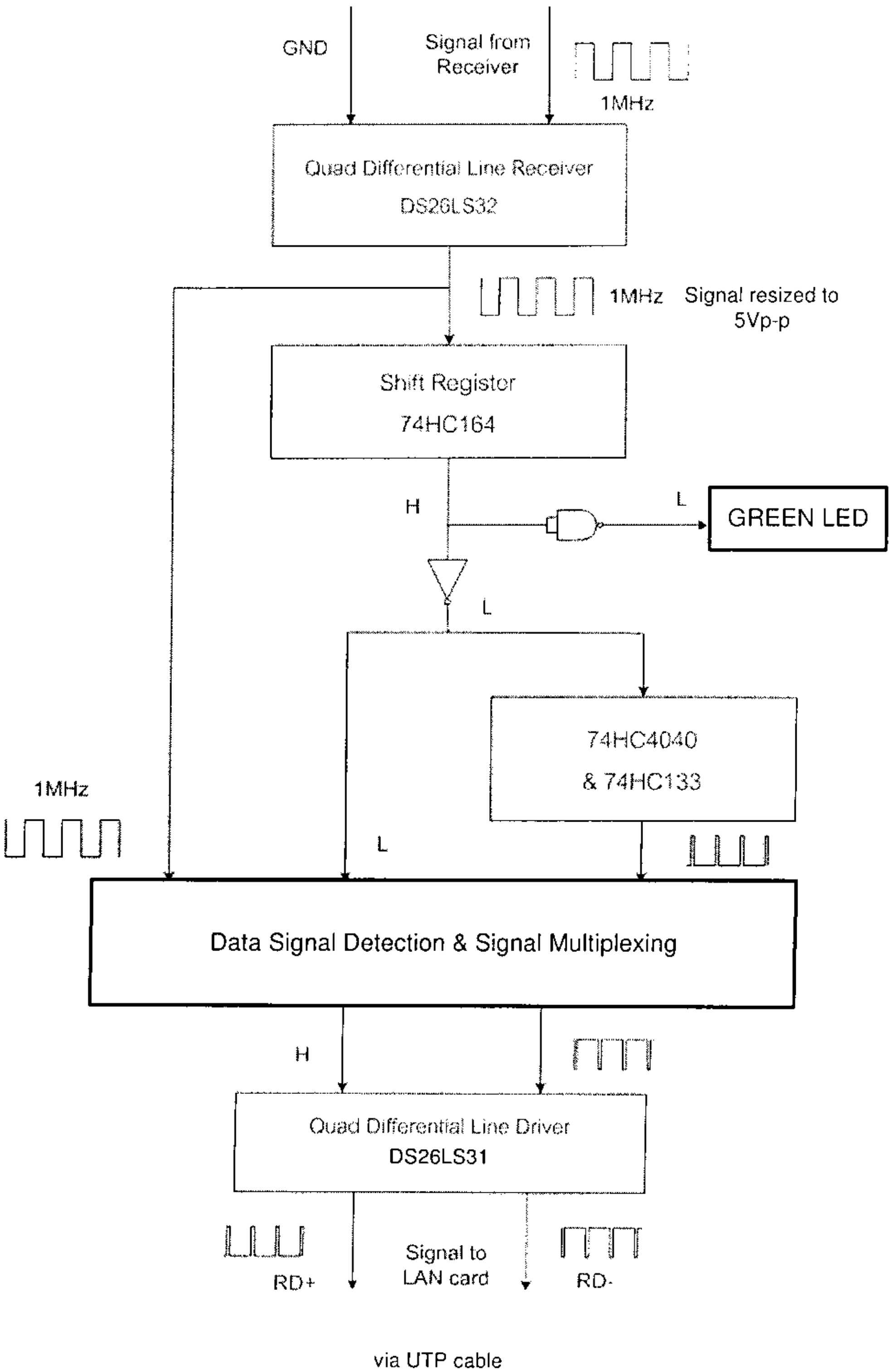


Fig.5.13: *Conceptual operational flow diagram of the receiver interface circuit without data signal*

5.5 Receiver interface circuit implementation

A comparator inside the same quad differential line receiver chip DS26LS32 employed in the transmitter interface is very handy for adjusting the size of incoming signal magnitude to 5Vp-p as shown in Fig.5.14. The input impedance has been 75-Ω matched to the receiver's output by forming resistors connected in parallel of 100Ω and 330Ω (the capacitor C109 is considered shorted at high frequency).

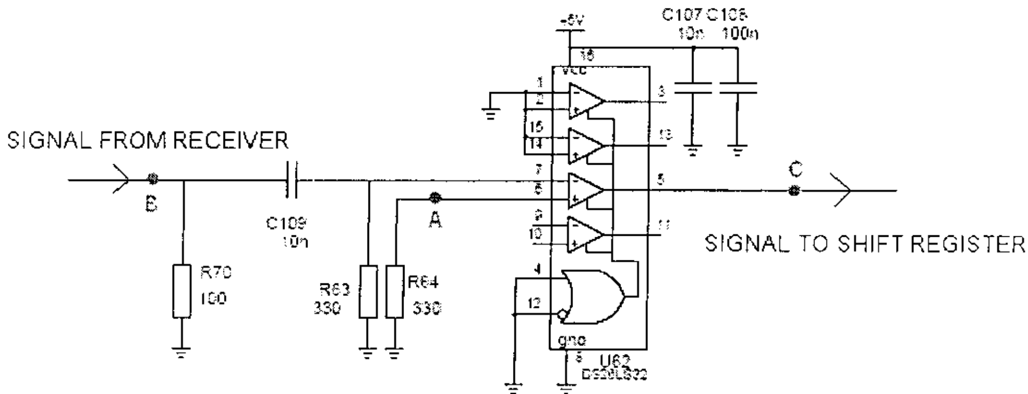


Fig.5.14: *A comparator inside DS26LS32 employed to resizing signal magnitude to $5V_{p\text{-}p}$*

Data signal detection is performed by a chain of shift registers 74HC164 and inverter Schmitt triggers (74HCT14) as shown in Fig.5.15 schematic.

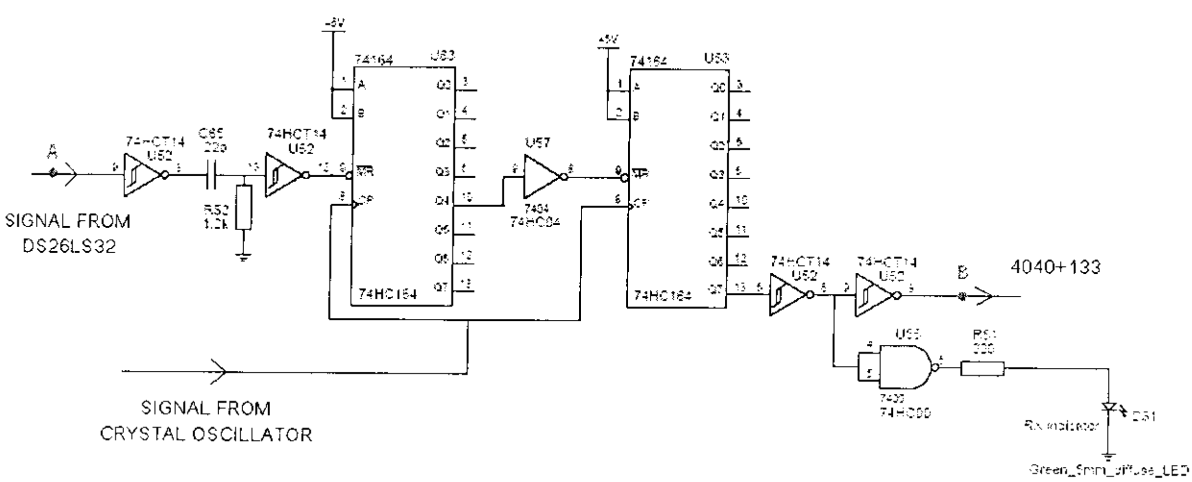


Fig.5.15: *A chain of 74HC164 shift registers employed for data signal detection.*

When there is no signal coming in, specific type of pulse has to be generated and fed to Ethernet card according to IEEE 802.3 standard. Such pulse generation can be achieved by utilizing the circuit in Fig.5.16. The circuit comprises two 12-stage binary ripple counters 74HC4040 [5.4] and two 13-input NAND gates 74HC133 [5.5] controlled by 16MHz clock signal.

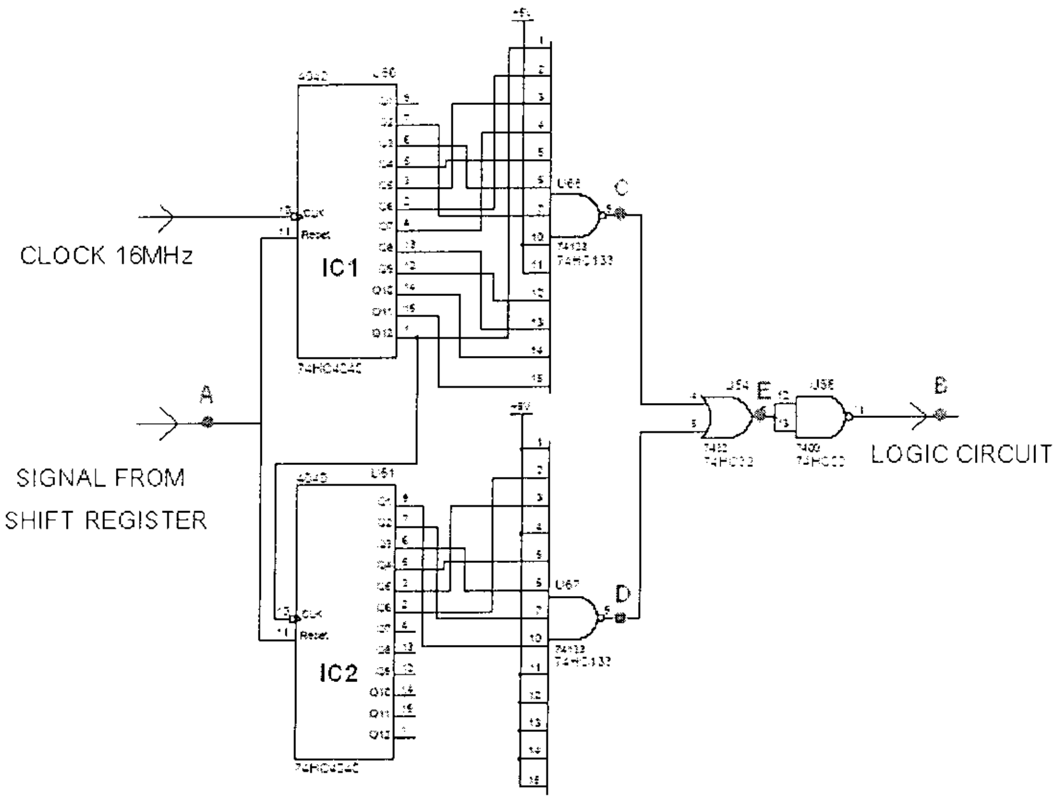


Fig.5.16: *Pulse generator for the receiver interface employing 74HC4040 and74HC133*

Either data signal or pulse is routed to the final stage depending on validity of data signal (logic level from Fig.5.15). This signal routing is done by the multiplexer shown in Fig.5.17. The output signals at points A and B are to drive the differential line driver IC DS26LS31 [5.6] of Fig.5.18 before sending to an Ethernet card. This differential line driver arranges differential signal RD+ and RD- for Ethernet card.

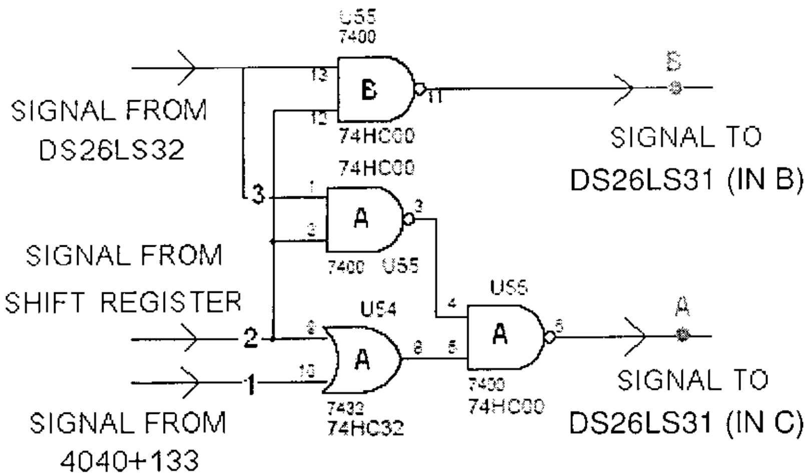


Fig.5.17: *Signal multiplexer for received signal selection and routing.*

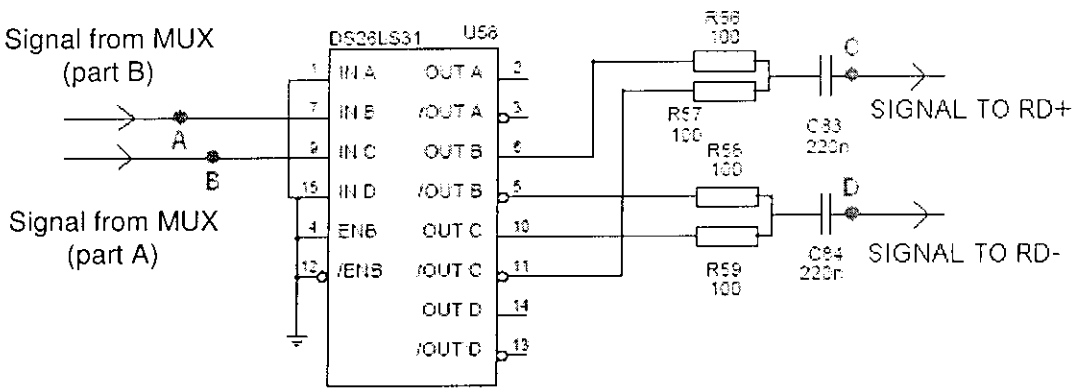


Fig.5.18: *Differential line driver IC DS26LS31 employed for signal conversion.*

5.6 Complete transmitter interface circuit

A simplified complete schematic of the receiver interface circuit is shown in Fig.5.19. Photo in Fig.5.20 illustrates the prototype interface circuit on a single printed circuit board housed inside a metal-sheet case. Measured received signals are fully recovered and processed as depicted in Fig.5.21 ready for launching into UTP cable to Ethernet card.

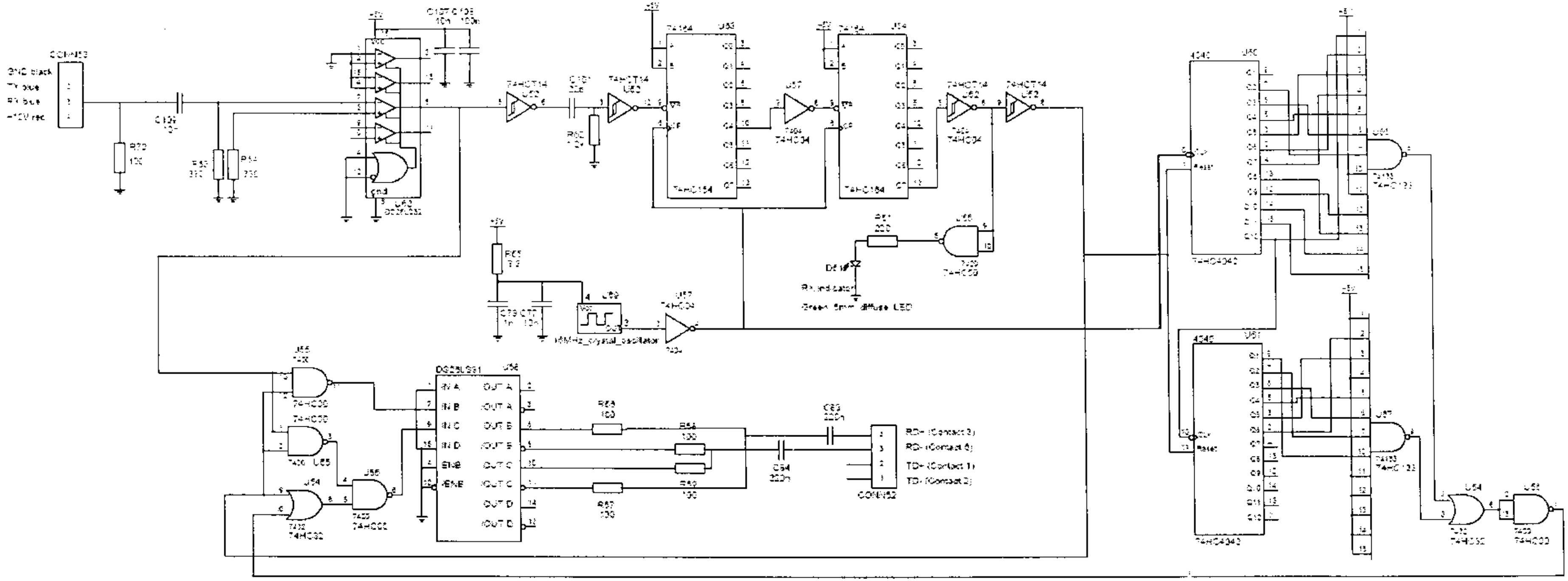


Fig.5.19: *A simplifier complete receiver interface schematic*

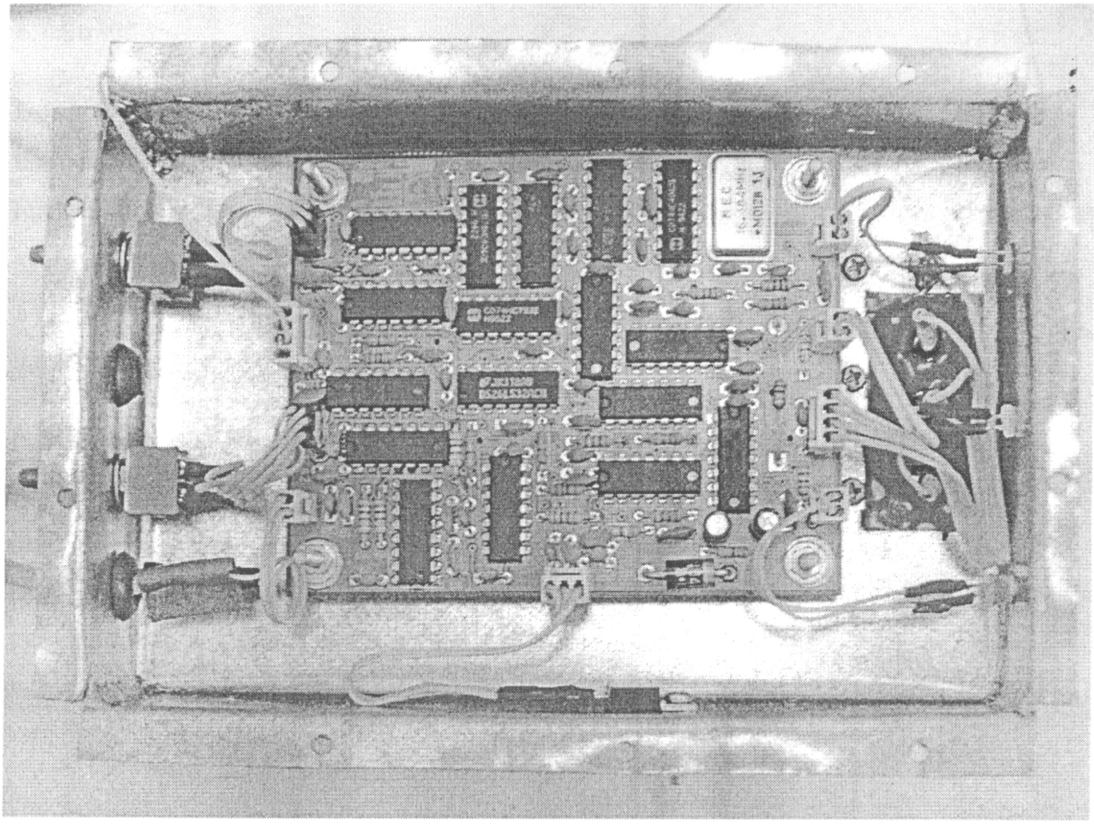


Fig.5.20: *The finished prototype of transmitter and received interface circuits housed on a single PCB.*

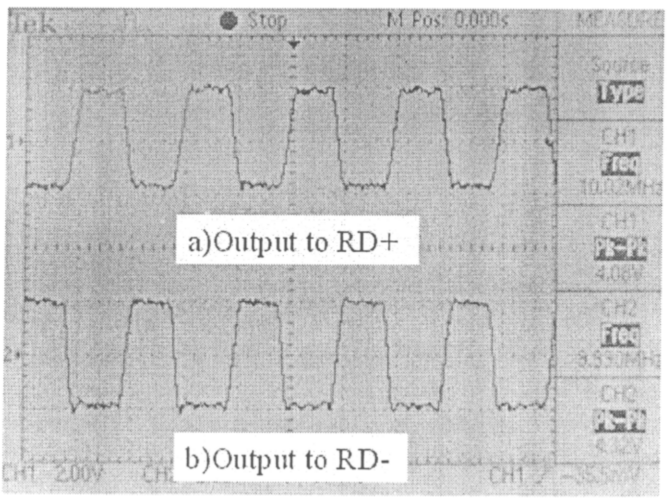


Fig.5.21: *Output signal at the receiver interface's differential line driver.*

5.7 Summary

Design of the interface circuits for the FSO transmitter and receiver has been discussed. Measured results confirm that the circuits behave in the way for which they have been intended. Following chapters deal with design of optical mechanics and system testing.

5.8 References

[5.1] Texas Instruments, Quadruple differential line receiver DS26LS32, datasheet.

[5.2] Philips, 8-bit serial-in/parallel out shift register 74HC164, datasheet.

[5.3] Philips, 4-bit binary ripple counter 74HC93, datasheet.

[5.4] Philips, 12-stage binary ripple counter 74HC4040, datasheet.

[5.5] Philips, 13-input NAND gate 74HC133, datasheet.

[5.6] Texas Instrument, Quadruple differential line driver DS26LS31, datasheet.

Chapter 6 System Testing

6.1 Introduction

This chapter explains a simple optical mechanic for light collimation and focusing in order to minimise beam divergence and increase a link distance. Such mechanics are built from easy-to-find materials to keep the prototype cost at minimum. An optical link test and demonstration by connection two computer terminals will be described.

6.2 Design of mechanical optics

Optical and lens mechanics play significant role in determining link distance according to

$$P_{R_x} = P_{T_x} \cdot \frac{A_{R_x}}{(\theta \cdot R)^2} \cdot \exp(-\alpha \cdot R) \tag{6.1}$$

where A_{Rx} is an optical receiver's area, R link distance (in km), θ is a beam divergence (in radians) and α is an atmospheric attenuation (dB/km). Small beam divergence θ results in a long link range and designer can minimise θ by employing biconvex lens at both transmitting and receiving ends for collimation and focusing respectively. In this work, no special techniques beyond elementary physics of lens have been applied to keep θ as small as possible. Bi-convex lens of 10-cm diameter with 22.5-cm focal length modified from a magnifying glass are used. Hence positions of such convex lens are as illustrated in Fig.6.1 and Fig.6.2 where the lens situate 22.5cm from the LED and photodiode respectively.

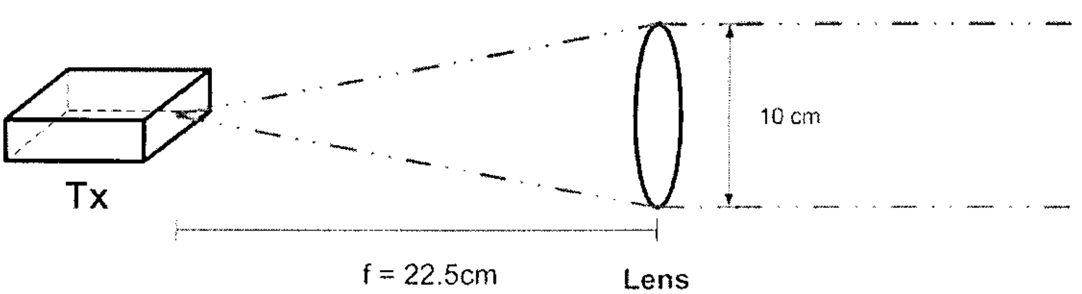


Fig.6.1: *Position of bi-convex lens of the transmitter*

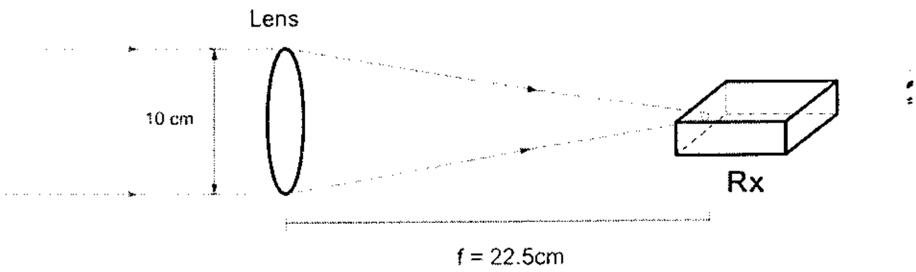


Fig.6.2: *Position of bi-convex lens of the receiver*

Cylindrical PVC pipes (11-cm diameter) are cut and used as optical loupes employed to house transmitters, receivers and lens as shown in Fig.6.3. The loupes have been designed such that the transmitter and receiver metal cases can be moved along the length of the loupe for collimating and focusing adjustment.

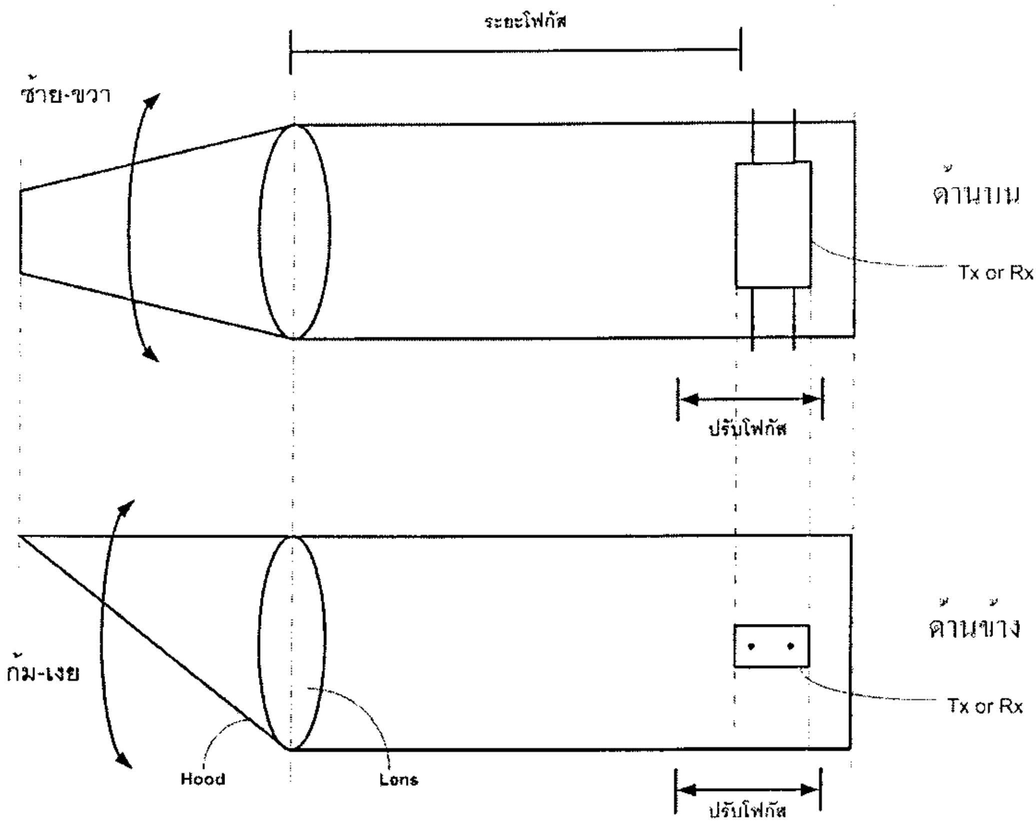


Fig.6.3: *Design of optical loupes for transmitter (Tx) and receiver (Rx).*

Optical loupe holders are designed from a few metal pieces to allow horizontal and vertical adjustment as depicted Fig.6.4. Photo of the finished FSO transceiver prototype mounted on a camera tripod at one end of the link is shown in Fig.6.5.

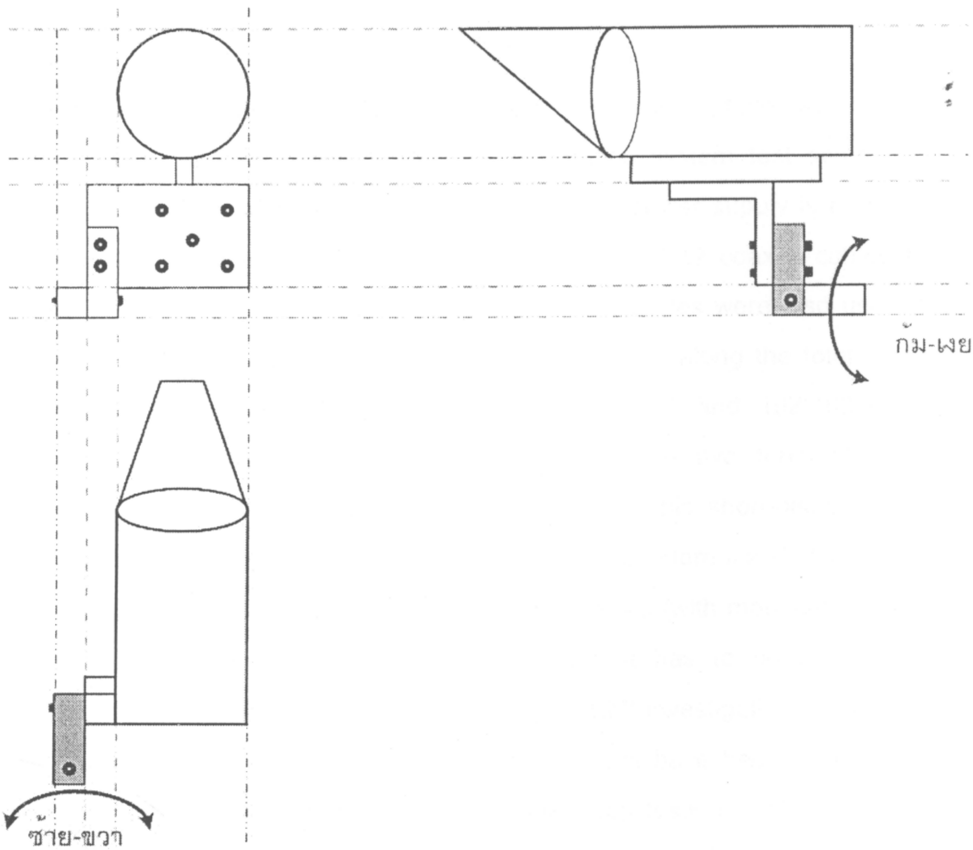


Fig.6.4: *Holder design for holding the optical loupes*

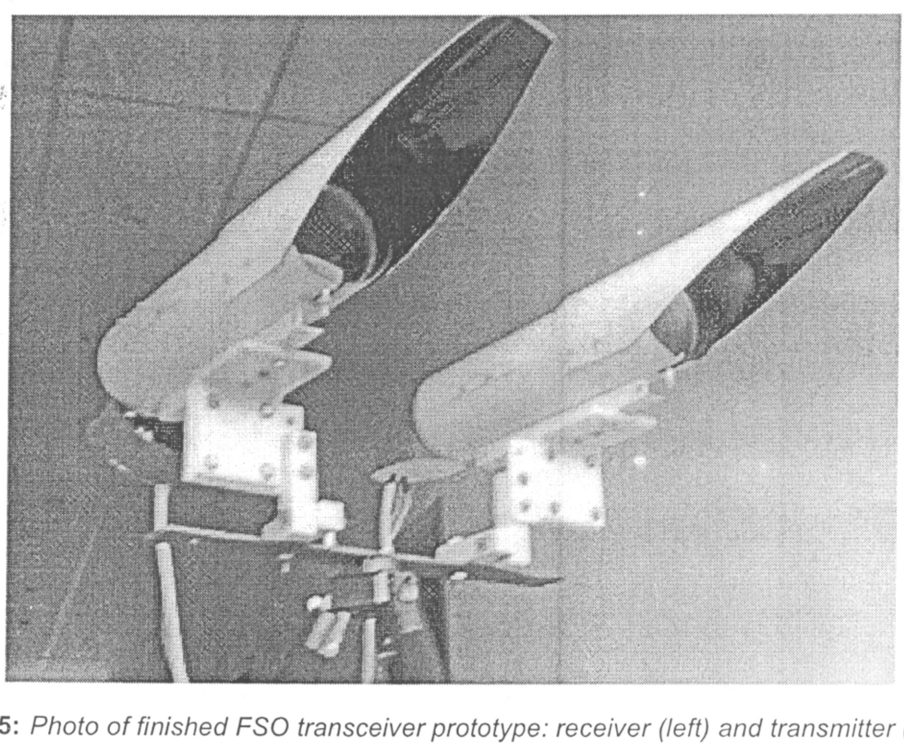


Fig.6.5: *Photo of finished FSO transceiver prototype: receiver (left) and transmitter (right)*

6.3 System testing

Initially the system was tested without distance-enhanced optical system in order to confirm transceiver functionality. A full-duplex 10Mbps system test setup to link two computer terminals is shown in Fig.6.6. A single 12-V power supply is needed at each end of the link. Besides employing two long shielded 75-Ω coaxial cables for signal connection between T_x, R_x and interface circuit, these cables were also used to supply 12V and ground to T_x, R_x via the outer shield which runs along the total length of the cable. The IPs have been assigned to be 192.168.1.1 and 192.168.1.2 with the connection type option set as 10Mb Full Duplex. The two terminals have been successfully linked as confirmed by *ping* test Fig.6.7. This short-distance testing (no collimation) has indicated an obvious electromagnetic interference (EMI) effect. That is, when the transmitters and receivers were properly sealed (with metal-sheet lids) the link distance has been doubled from 70cm to 140cm. It has to be noted that proper techniques and equipments are needed for serious EMI investigation of the transceiver. Owing to a robust TCP/IP protocol, various applications have been successfully tested to verify stability of the implemented optical link. Such testing applications include file transfer, virtual network computing (VNC) [6.1], Counter Strike on-LAN game,

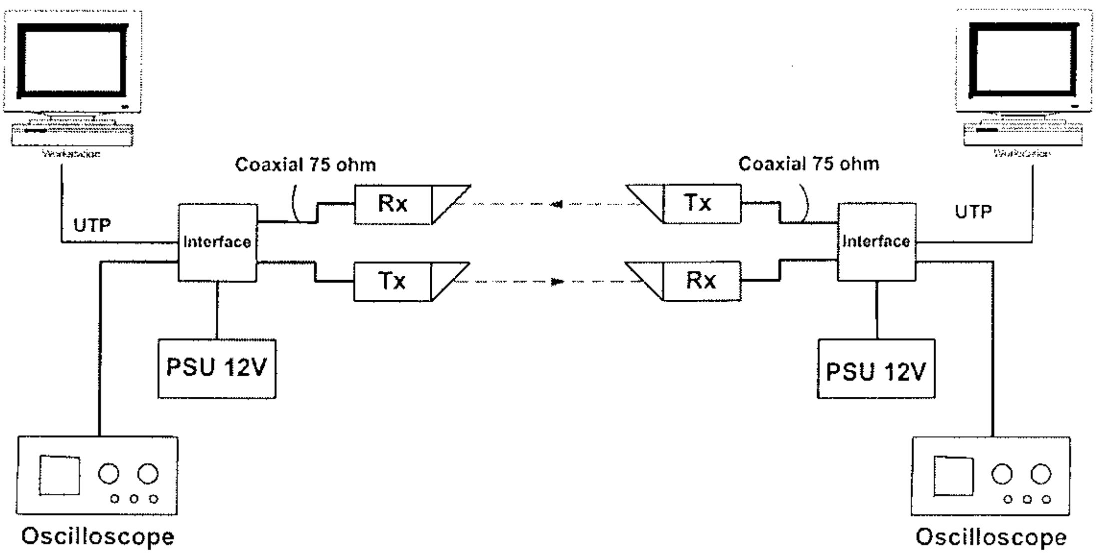


Fig.6.6: *Transceiver test setup*

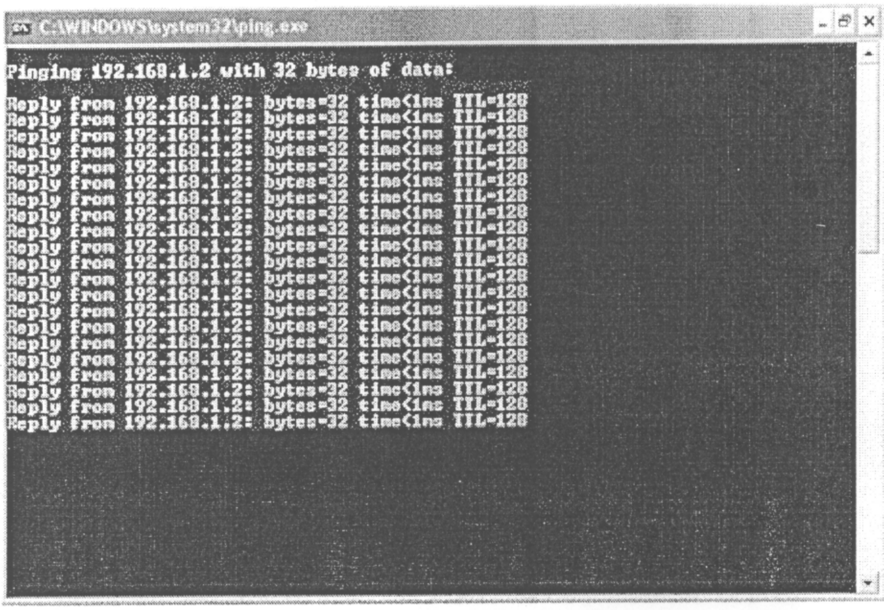


Fig.6.7: *Ping command testing confirms successful optical link*

With enhancing optical mechanics, a long-range test was carried out between the radio tower of Satang Mongkolsuk, Faculty of Engineering building and the eastern side of Faculty of Environmental Management (level 8) as depicted in Fig.6.8 in which the distance was approximated to be at 300 metres. Photo of a one-side setup is also shown in Fig.6.9. Connection activities can be monitored by using Ethereal software [6.2] as illustrated in Fig.6.10. It is clear that with help of a simple optical system arrangement, the link range has been enhanced by over 200 times.

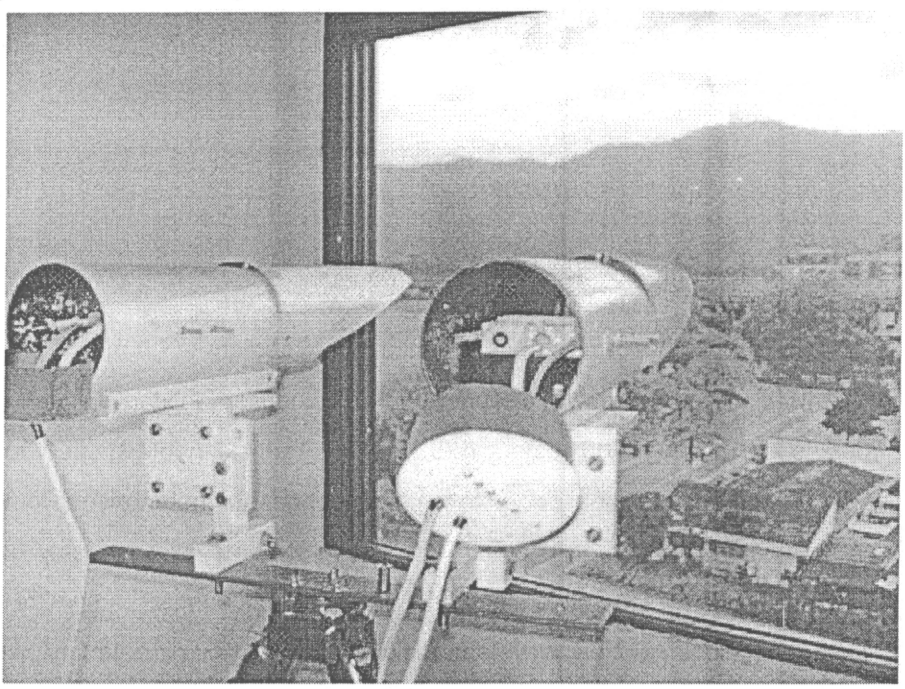


Fig.6.8: *Long-distance testing*

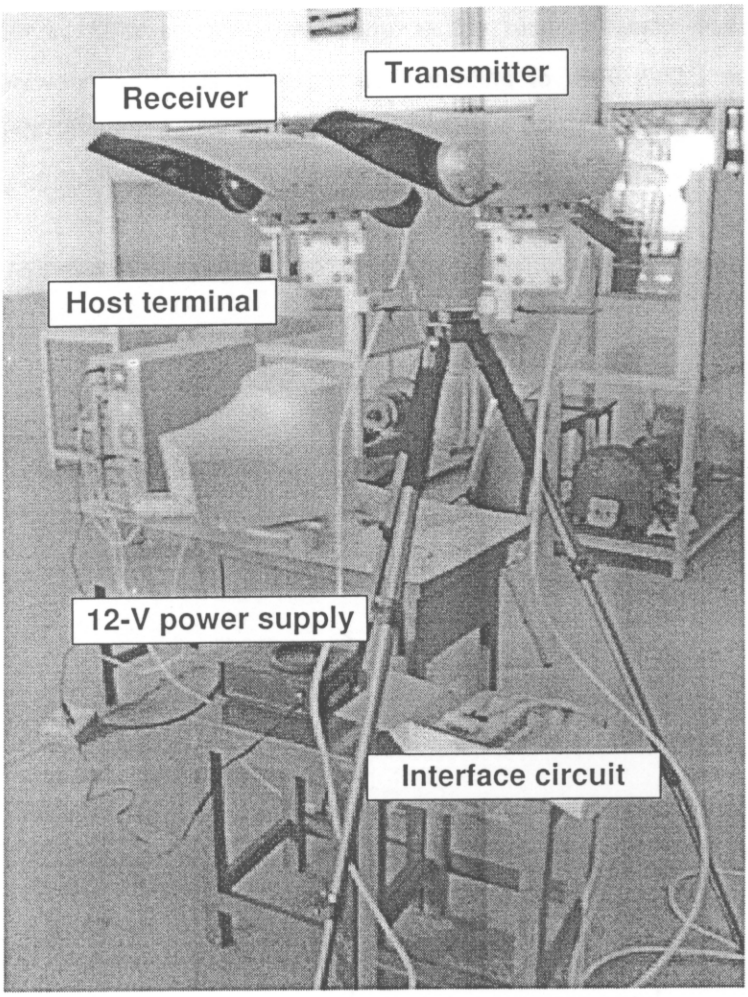


Fig.6.9: *A complete system setup on one-side.*

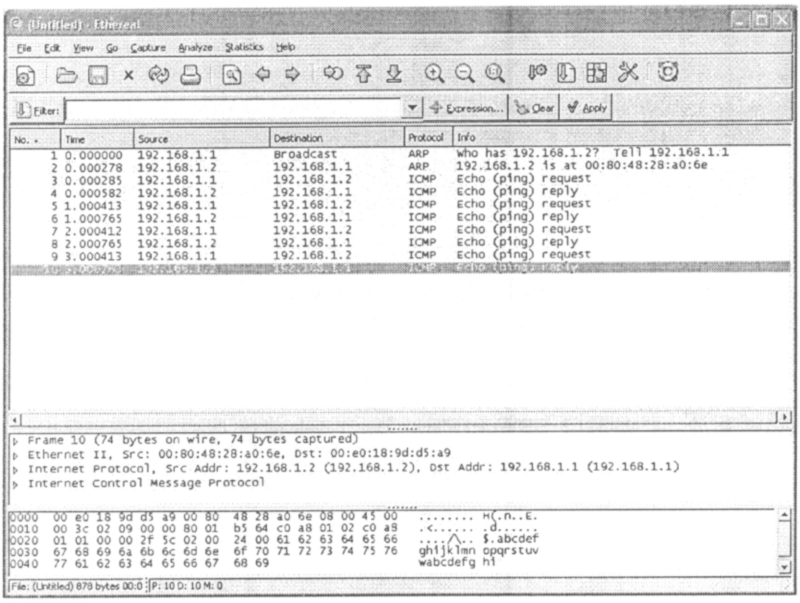


Fig.6.10: *Capture screen from Ethereal for monitoring connection activities.*

Fig.6.11 displays 1MHz square wave signal at the receiver when there is no data transmitted between terminals as expected according to IEEE 802.3 standard. This particular signal is very useful during installation and aiming. Table 6.1 summarises performances of one transceiver.

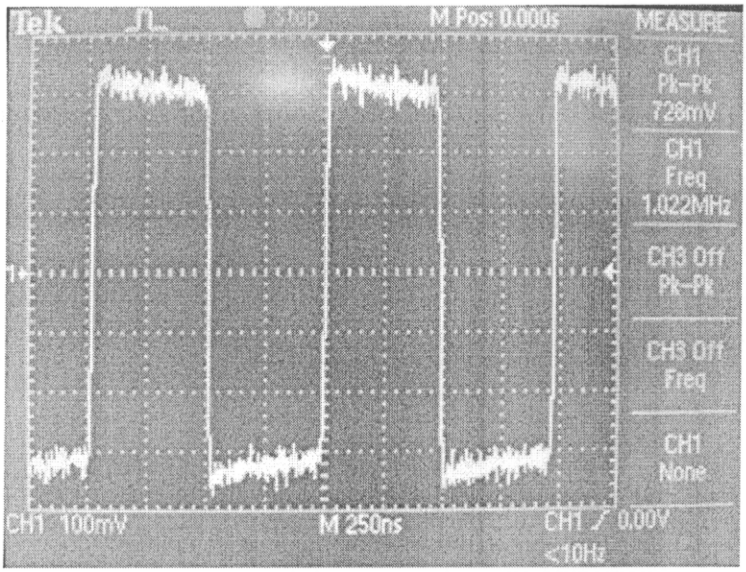


Fig.6.11: *Received 1MHz signal when no data is being transmitted.*

Table 6.1: *Summary of the transceiver performances*

Link Speed	10Mbps
Standard	IEEE802.3, Full duplex
Operating Wavelength	635 nm
Link distance	300 metres
Power supply	12 V
Power consumption	2.4 W

6.4 Summary

Optical mechanics and system testing have been described. The implemented transmitters, receivers, and interface circuits were integrated to form a fully functional free-space optical link. The system was successfully tested to link two computer terminals situated 300-metre apart at 10Mbps, full duplex.

6.5 References

[6.1] Virtual Network Computing (VNC), http://www.vnc.com.

[6.2] Ethereal – Network Protocol Analyzer, http://www.ethereal.com.

Chapter 7 Conclusion and Future Work

7.1 Conclusions

Significant works achieved in the design of a free-space optical transceiver research are briefly concluded:

- Transmitter circuits for FSO transceivers have been designed, confirmed with simulation, implemented and successfully tested.
- Receiver circuits for FSO transceivers have been designed, confirmed with simulation, implemented and successfully tested.
- Interface circuits, which bridge transmitters, receivers with computer terminal Ethernet cards, have been designed and experimentally tested.
- Transmitters, receivers, and interface circuits have been integrated to form two complete free-space optical transceivers. With appropriate optical and lens mechanics for link range enhancement, the transceivers allowed successfully 10Mbps full-duplex TCP/IP communication over a distance of 300 metres. This confirms an FSO system as a viable alternative and support for wireless Ethernet communication.

7.2 Future work

The system test has shown a promising result which should stimulate more research on optical wireless for high-speed data communication. Feasible future works are listed here:

- Link distance could be extended beyond the currently achieved range (300 metres) by employing additional transceivers (Fig.7.1) to behave as repeaters as well as providing an indirect line-of-sight.
- The current size of the prototype transmitter could be reduced if a low-cost laser pointer integrated with micro-lens is employed instead of LEDs. This is because there is no further need to have large bi-convex lens for light collimation since this is inherently accomplished by the micro-lens of the laser pointer. Consequently, the transmitter driving circuitry has to be redesigned to be able drive a laser diode, especially, the ability to compensate for temperature drift.
- The receiver circuit could be improved to provide a pseudo-differential structure so that any common-mode interfering signal can be effectively suppressed, for example, that from a power supply.

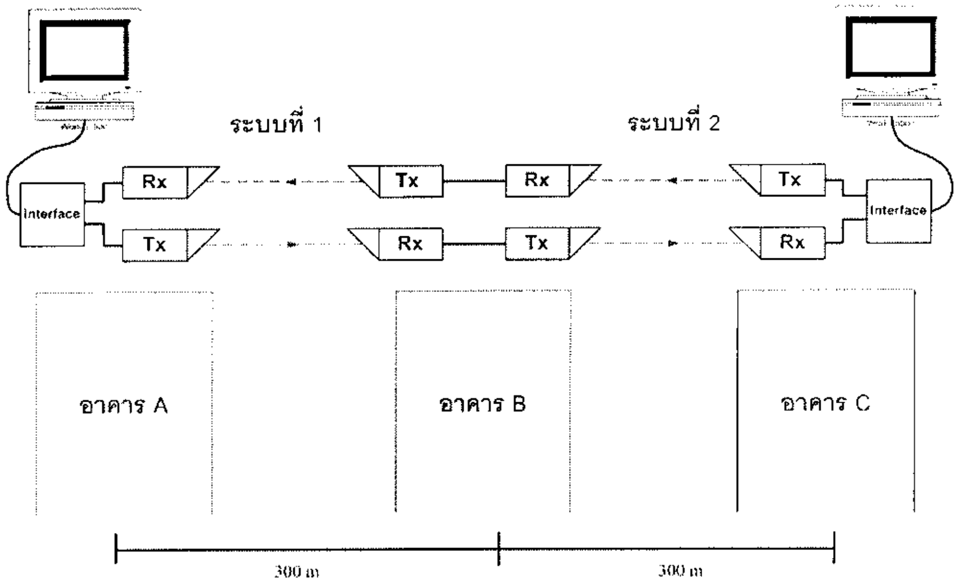


Fig.7.1: *Link range can be increased by employing additional transceivers*

7.3 References

[7.1] B. Razavi, *Design of Integrated Circuits for Optical Communications*, McGraw-Hill, New York 2003.

บทความวิชาการที่เผยแพร่

1. ภาณุมาส คำสัตย์, วรัตม์ รื่นรักษา และ Karel Kulhavy "ระบบไร้สายผ่านแสงสำหรับการสื่อสารข้อมูลความเร็วขนาดปานกลาง," การประชุมวิชาการทางวิศวกรรมไฟฟ้า ครั้งที่ 28, 20-21 ตุลาคม 2548.
2. Karel Kulhavy, Warat Reunraksa, Pavita Wiriyacosol, and Phanumas Khumsat, "Low-Cost Free-Space Optical Transceiver for 10Mbps Data Communications," Proceedings of 2005 International Conference on Electromagnetic Compatibility, July 26-27, 2005, Phuket, Thailand.