

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

**SUDAN UNIVERSITY OF SCIENCE AND  
TECHNOLOGY  
COLLEGE OF POST GRADUATE STUDIES**

# **Design And Implimentation Of Rf Optical Link**

**A THESIS SUBMITTED FOR THE FULFILLMENT  
OF THE DEGREE OF PHILOSOPHY OF  
DOCTORATE IN LASER PHYSICS**

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\*ثم ارجع البصر حركتين ينقلب اليك  
البصر خاسئاً وهو حسير\*

صدق الله العظيم

سورة الملك الآية 4

# **DEDICATION**

I dedicate this thesis to the soul of my father, to my mother, to my wife and children, to my brothers and sisters, to my friends.

# ACKNOWLEDGEMENT

At first I thank **ALLAH Who** gives me the power to complete this work.

I would like to express my sincere appreciation to my supervisors, Prof. Dr. **Khalil I. Hajim**, and Dr. **Kais A. ALNaimee** for their instructions, encouragement and assistance throughout this work. My deep gratitude and thanks to Prof. Dr. **Nafia Abdelatif**, Dr. **Hussein A. Jawad**, Ms. **Sheelan K. Towfig**, and all the **ILOG** members for their comments and help.

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# **Abstract**

The separation between the RF antenna and the rest of the equipments of radar is considered as an important process. It is possible to achieve this task by converting the radar signals into corresponding optical signals, and sending it through an optical fiber in order to protect the personnel and instruments in critical positions.

In this work, an RF optical communications system was designed to achieve this objective. The modulated RF signal was coupled via a matching circuit into optical fiber system. The output signal was detected.

The power budget, maximum distance and maximum bit rate for the optical communication system was calculated. The efficiency of the optical RF and optical communication system was proved using the experimental results.

Definite agreement between modulated RF signal and the output signal at the end of the fiber was achieved.

## المخلص

الفصل بين الهوائي وبقية المعدات في المنظومات الميكروية يعتبر من التهيأت المهمة. ويمكن انجاز هذه المهمة بتحويل الاشارة المايكروية المضمنه الي اشارة ضوئية متوافقة معها وارسالها خلال منظومة ليف بصري الي مواقع بعيدة بغرض حماية الاشخاص والاجهزة في المواقع الحساسة.

في هذا البحث تم تصميم منظومة للقيام بالعمل الموصف اعلاه حيث ربط خرج الاشارة الميكرويه المضمنة الي منظومة ليف بصري واستلمت الاشارة الخارجة من مستقبل منظومة الليف البصري، وتم حساب القدرة الصافية واكبر مسافة واقصى جريان للتصميم الضوئي حيث اثبتت كفاءة دائرة اتصال الليف البصري. وتم الحصول علي توافق جيد بين الاشارة المايكروية المضمنة والاشارة النهائية.

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## List of symbols

Symbol	Description
$\mu m$	Micro-meter, measure unit for wavelength = $10^{-6}$ m
$\Delta v$	The magnitude of quantizing levels
a	Core radius of the fiber
A	Area of the light emitter
$A_v$	Voltage gain
B	The bandwidth of analog signal
BER	Bit error rate
BPS	Bit per unit second
dB	Decibel, gain or attenuation unit
dBm	Power unit references to 1 mili-watt
GaAIAs	Gallium aluminum arsenide alloys
InGaAs	Indium gallium arsenide
$i_n$	Thermal noise current in photodiode detector
$i_p$	Generated current in photodiode detector
$n_0$	Refractive index of air
$n_1$	Refractive index of fiber core (high)
$n_2$	Refractive index of fiber cladding (low)
nm	Nano-meter, measuring unit of wavelength = $10^{-9}$ m
OP AMP	Operational amplifier
$P_t$	Transmitted power
$P_{res}$	Power received sensitivity
$R\lambda$	Responsivity of the photodiode detector



TTL	Transistor transistor logic circuits
MOS	Metal oxide semiconductor
A	Fiber refractive index profile
$\theta_c$	Acceptance angle
$\Phi_1$	Incident ray angle
$\Phi_2$	Refracted ray angle
$\Phi_c$	Critical angle
V <sub>r</sub>	Target radial velocity
E	Elevation angle
P <sub>min</sub>	Minimum received power
R <sub>L</sub>	Load resistance
S/N	Signal to noise ratio
S	Pulse duration
$\Delta$	Core-cladding difference
$\alpha$	Fiber refractive index profile
$\alpha_r$	Radiation attenuation coefficient
$\lambda$	Wavelength
$\lambda_0$	Wavelength in space
D	Detectivity
N.A	Numerical apperture
B	Azimuth angle

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**DESIGN AND  
IMPLIMENTATIO  
N  
OF RF OPTICAL  
LINK**

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- **INTRODUCTION**
  - \***OPTICAL FIBER AND LASER PRINCIPLES**
  - \***MICROWAVE PRINCIPLE**
- **THE AIM OF THE WORK**
- **THE EXPERIMENTAL WORK**
  - \***THE MICROWAVE SYSTEM**
  - \***THE OPTICAL FIBER SYSTEM**
- **RESULTS**
- **CONCLUSIONS AND FUTURE WORKS**

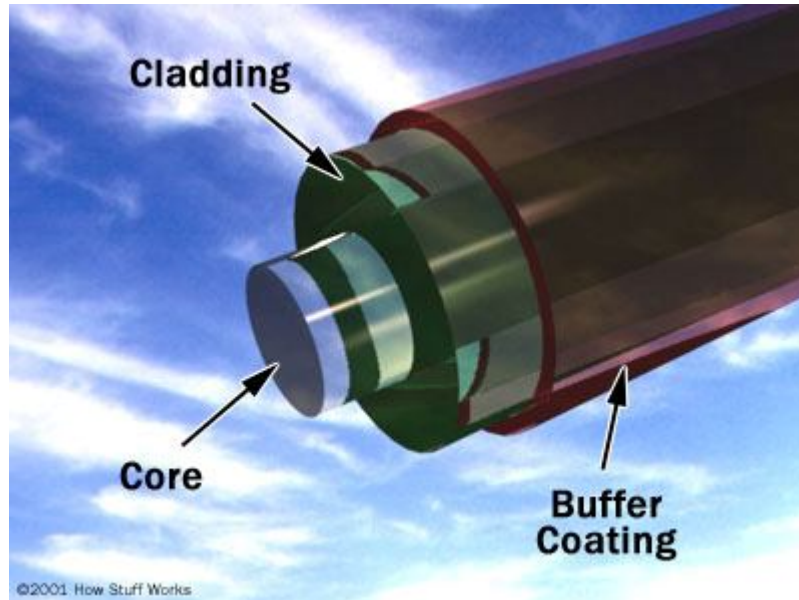


# INTRODUCTION

The separation between the RF antenna and the rest equipment of the radar is considered as an important process. It is possible to achieve this task by converting the radar signal into corresponding optical signal, and sending it through optical fiber in order to protect the personal and instruments in critical positions.

## OPTICAL FIBER AND LASER PRINCIPLES:

**Fiber optics** are long, thin strands of very pure glass or polymer about the diameter of a human hair. They are arranged in bundles called **optical cables** and used to transmit [light](#) signals over long distances.



Parts of a single optical fiber

If you look closely at a single optical fiber, you will see that it has the following parts:

- **Core** - Thin glass center of the fiber where the light travels
- **Cladding** - Outer optical material surrounding the core that reflects the light back into the core
- **Buffer coating** - Plastic coating that protects the fiber from damage and moisture

Hundreds or thousands of these optical fibers are arranged in bundles in optical cables. The bundles are protected by the cable's outer covering, called a **jacket**.

## FIBER OPTIC DATA LINKS

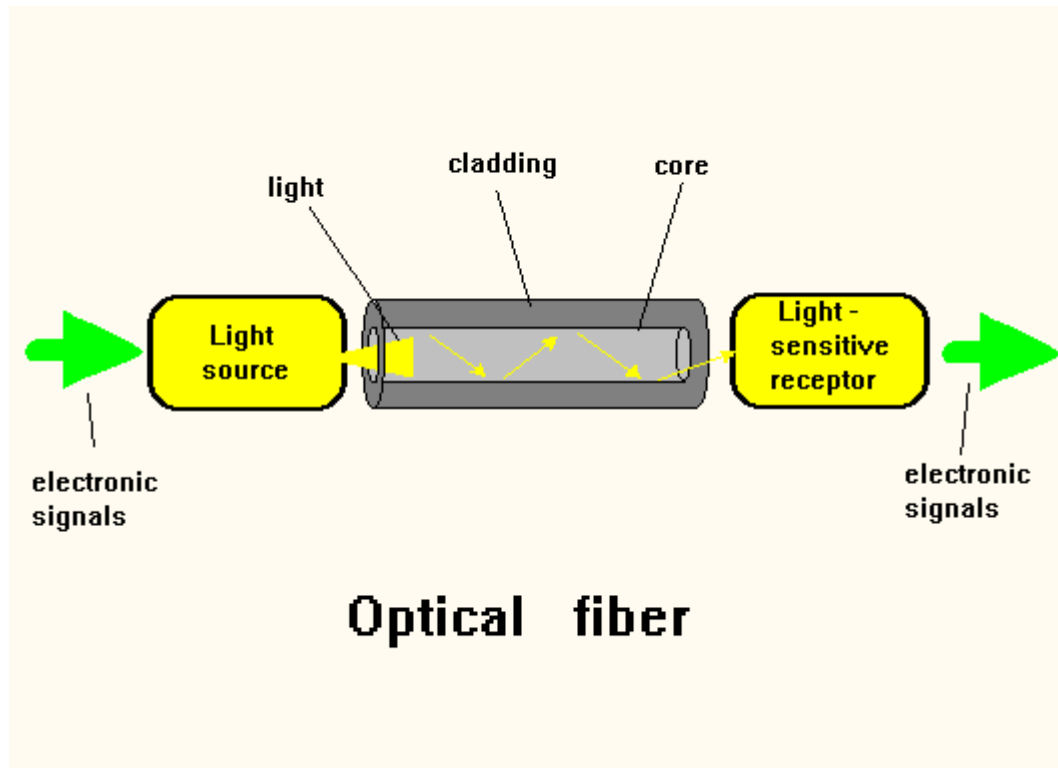
A fiber optic data link sends input data through fiber optic components and provides this data as output information. It has the following three **basic functions**:

- To convert an electrical input signal to an optical signal.
- To send the optical signal over an optical fiber
- To convert the optical signal back to an electrical signal

A fiber optic data link consists of three parts—**transmitter, optical fiber, and receiver**.

Figure 1 is an illustration of a fiber optic data-link connection. The transmitter, optical fiber, and receiver perform the basic functions of the fiber optic data link. Each part of the data link is responsible for the successful transfer of the data signal. A fiber optic data link needs a transmitter that can effectively convert an electrical input signal to an optical signal and launch the data-containing light down the optical fiber.

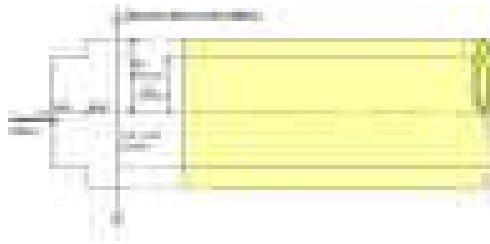
A fiber optic data link also needs a receiver that can effectively transform this optical signal back into its original form. This means that the electrical signal provided as data output should exactly match the electrical signal provided as data input.



There are two main fibre types:

- (1) Step index (multimode, single mode)
- (2) Graded index (multimode)

Step Index Fibre:



**Figure 6 - Step Index Fibre**

Step index fibre is so called because the refractive index of the fibre 'steps' up as we move from the cladding to the core of the fibre. Within the cladding the refractive index is constant, and within the core of the refractive index is constant.

### *Multimode*

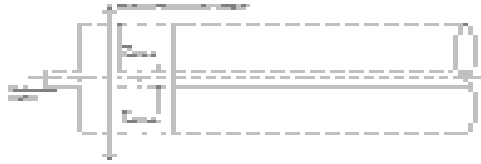
Although it may seem from what we have said about total internal reflection that any ray of light can travel down the fibre, in fact, because of the wave nature of light, only certain ray directions can actually travel down the fibre. These are called the "**Fibre Mode**". In a multimode fibre many different modes are supported by the fibre. This is shown in the diagram below.



## **Figure 7 Multimode fibre**

### ***Single Mode***

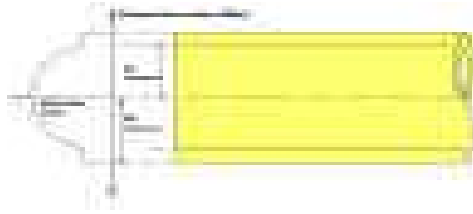
Because its core is so narrow Single Mode fibre can support only one mode. This is called the "Lowest Order Mode". Single mode fibre has some advantages over multimode fibre which we will deal with later



### **Single Mode Fibre**

### ***Graded Index Fibre***

Graded Index Fibre has a different core structure from single mode and multimode fibre. Whereas in a step-index fibre the refractive index of the core is constant throughout the core, in a graded index fibre the value of the refractive index changes from the centre of the core onwards. In fact it has what we call a Quadratic Profile. This means that the refractive index of the core is proportional to the square of the distance from the centre of the fibre.



**Figure 9 - Graded Index Fibre**

Graded index fibre is actually a multimode fibre because it can support more than one fibre mode. But when we refer to "multimode" fibre we normally mean "step index multimode".

## **INTRODUCTION**

It is desirable for vital reasons to locate the sites of the signal analysis and decision making side far away from the microwave detection unit with secure linkage. In this work a system will be designed and arranged to carry out this function. The goal is to separate the microwave receiving unit from sites of other units to protect the equipments and personal in some critical situation.

In this work the RF optical communications system is designed to achieve the target. The modulated RF signal is coupled via a matching circuit into optical fiber system. And the output signal is detected.

The power budget, maximum distance and maximum bit rate for the optical communication system was calculated. The



efficiency of optical RF optical communication system is proved using the experimental results.

Definite agreement between modulated RF signal and the output signal is achieved.

## **EXPERIMENTAL WORK**

The objective of the present work is to construct a microwave observation unit using a diode laser and optical fiber.

The main units are:

- **The microwave system.**
- **The matching circuit.**
- **Optical fiber system.**

Figure 1 shows the block diagram of the whole system components.

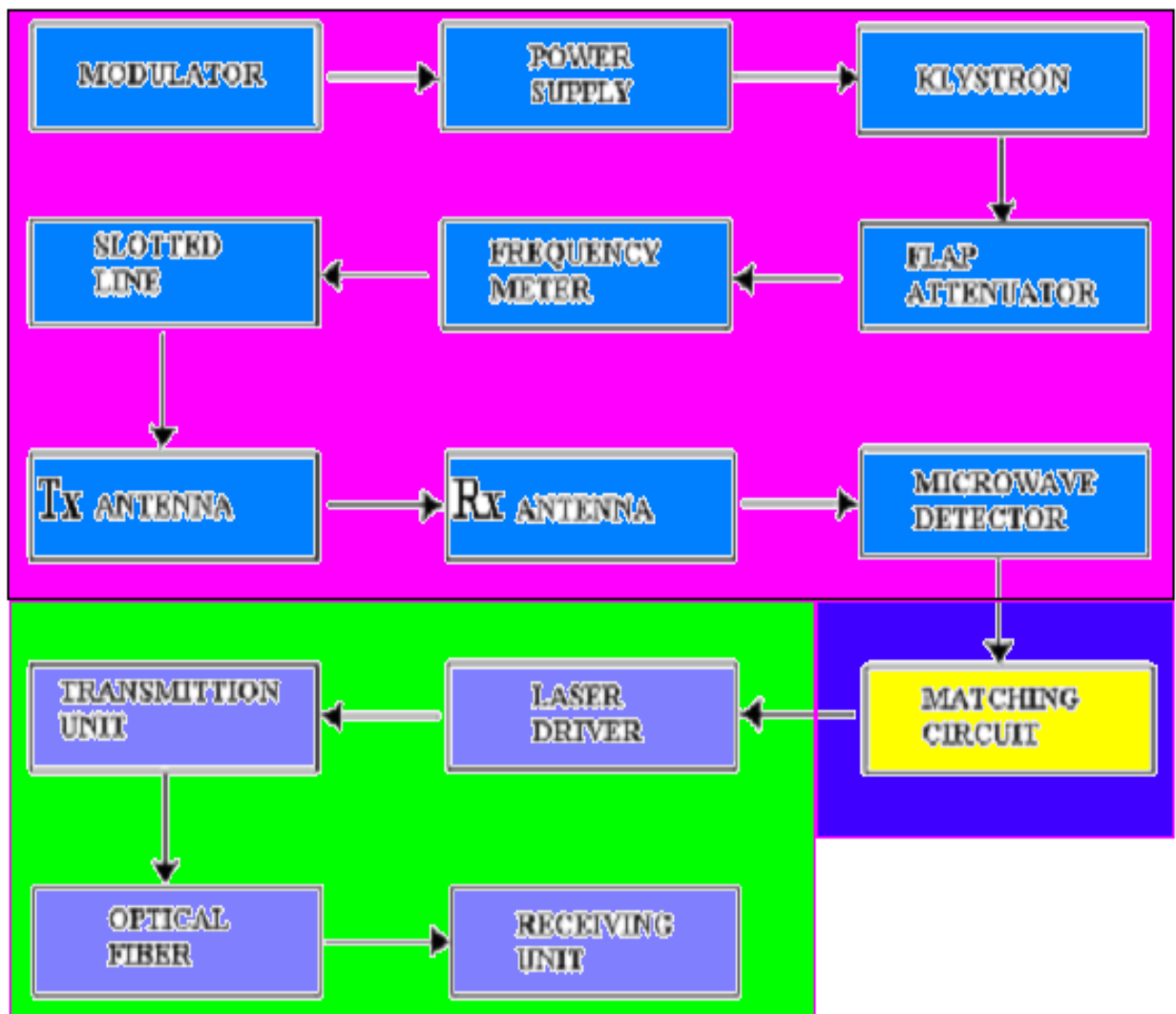


Figure 1 The block diagram of the whole system

### **Microwave system:**

The microwave system used in the present work provides a microwave signal of 10.687GHz frequency, which is modulated with a square wave signal at a frequency of 5 kHz.

The system consists of:

- **modulator**
- **power supply**
- **RF source**
- **flap attenuator**
- **slotted line, antennas**
- **detector**

Figure 2 shows a schematic diagram of the microwave system.

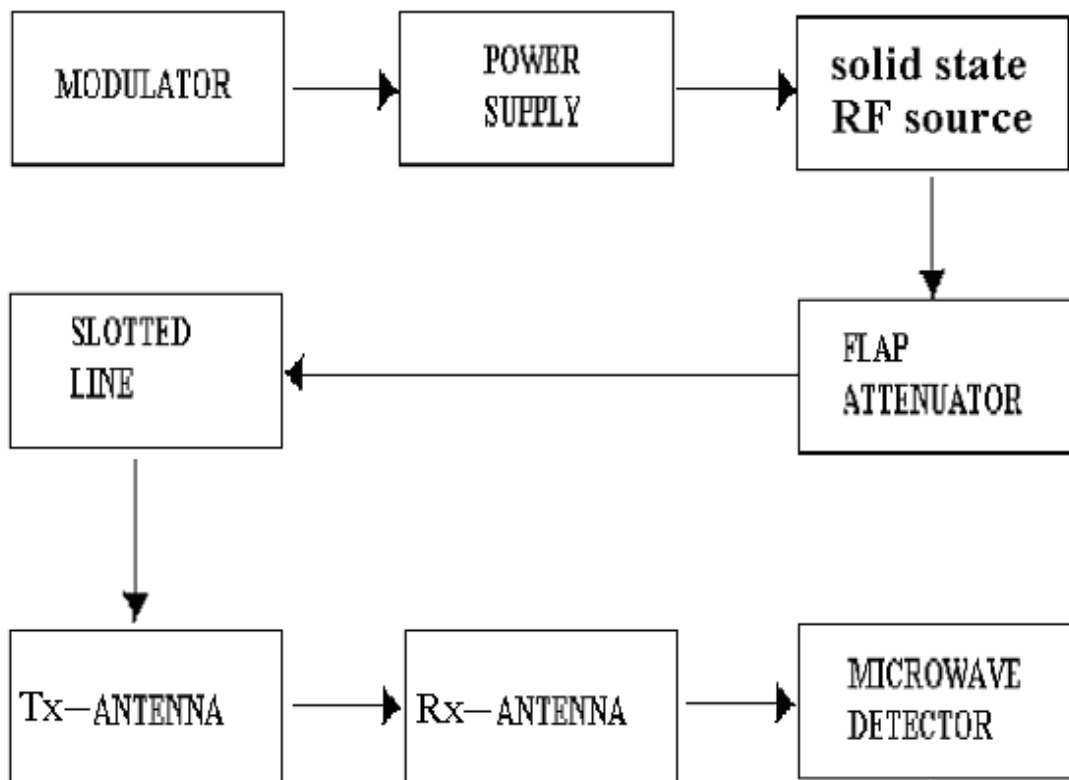


Figure 2 The block diagram of the microwave system



A photographic reproduct for the whole RF system.

### **The matching circuit:**

The main obstacle faced here is that the output voltage of the available microwave detector signal is between 50 mV and 200 mV with low current. This is below the required voltage which is 5 volts, this is the minimum voltage necessary to operate the diode drive circuit to overcome the above problem. Double function circuit must be constructed and used for the current and the voltage of the microwave signal to amplify it. This circuit consists of two stage amplifiers (OPA mp) of HI 741 type as shown in figure 3.9. The constructed circuit is used to match the end front of the microwave unit to the front of the laser diode circuit. This is to ensure that no drop in the signal coming from the microwave detector occurs.

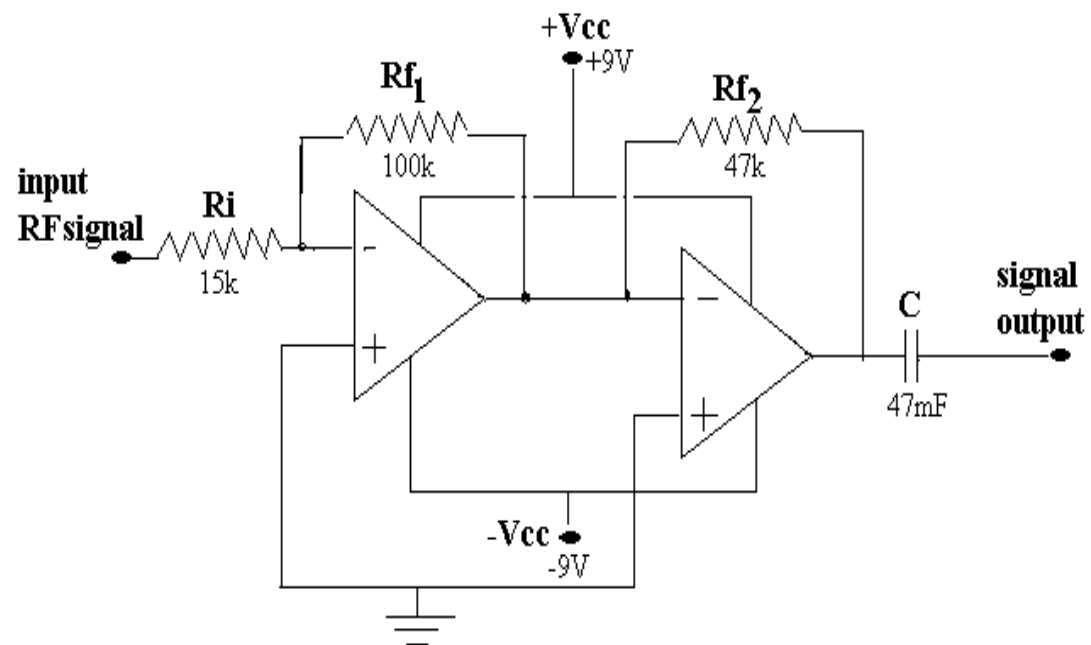
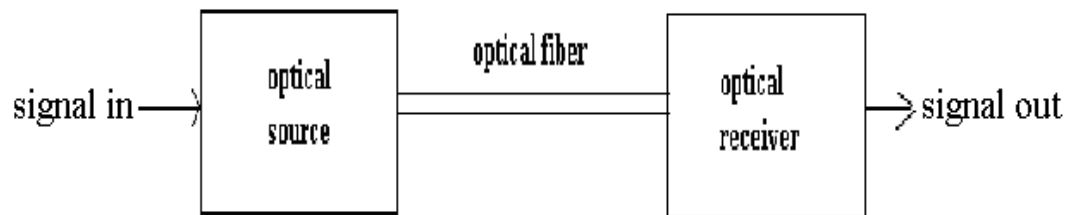


Figure 3.9 The matching circuit

The gain of the first amplifier is about 6.67, and the gain of the second amplifier is about 47. It means that the microwave detected signal is amplified to about 280 times.



## **Optical fiber communication system:**

- **Optical transmitter unit:**
- **Optical fiber receiver unit:**
- **Optical fiber:**





A Photograph of the reproductive RF optical fiber system.

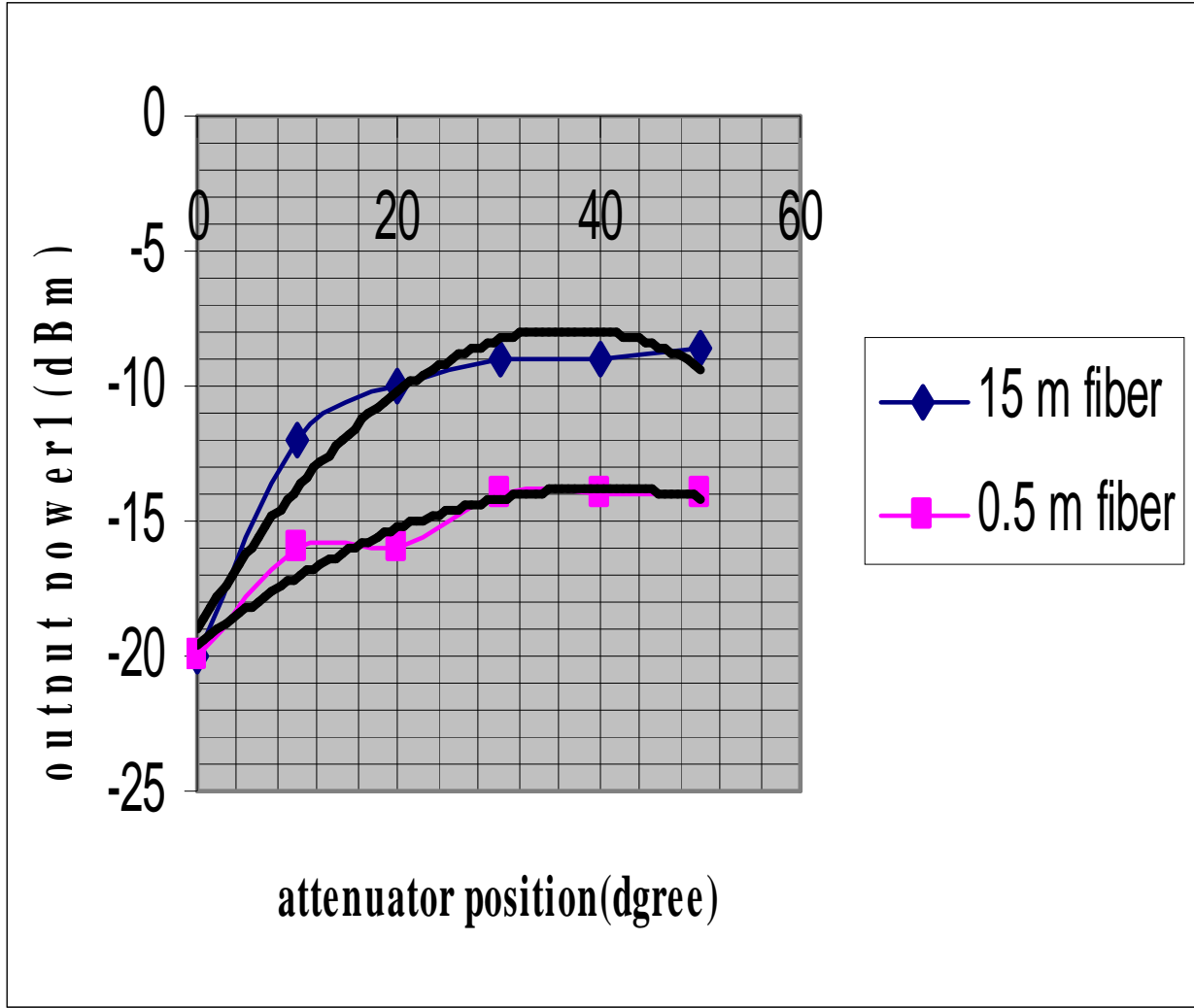
## **RESULTS AND DISCUSSION**

- The calculated and practical results for the RF optical communication system will be presented.
- The power budget of the RF optical fiber system, maximum distance with transmitting 5 k pulse per second, maximum bit rate and the maximum distance of the optical link will be illustrated.
- The performance parameters describing the employed measuring system will be studied. Finally comments on the results will be viewed in the discussions and conclusions.

**Microwave system performance:**

**The microwave detection:**

The IN23 microwave output detector is used in the present work. This detector is fabricated for low level detection. The crystal diode detector is mounted in the center of the waveguide. The detector output voltage is between 0.05 – 0.25 V at frequency of 5 kHz set by the modulator. To examine the behavior of the received microwave signal, the variable attenuator is used. An experiment is carried out in which the microwave detector output power is recorded for different attenuator position (i.e. different attenuation angle). The relation between the attenuator position and the microwave output power detector is shown in figure 4.1.



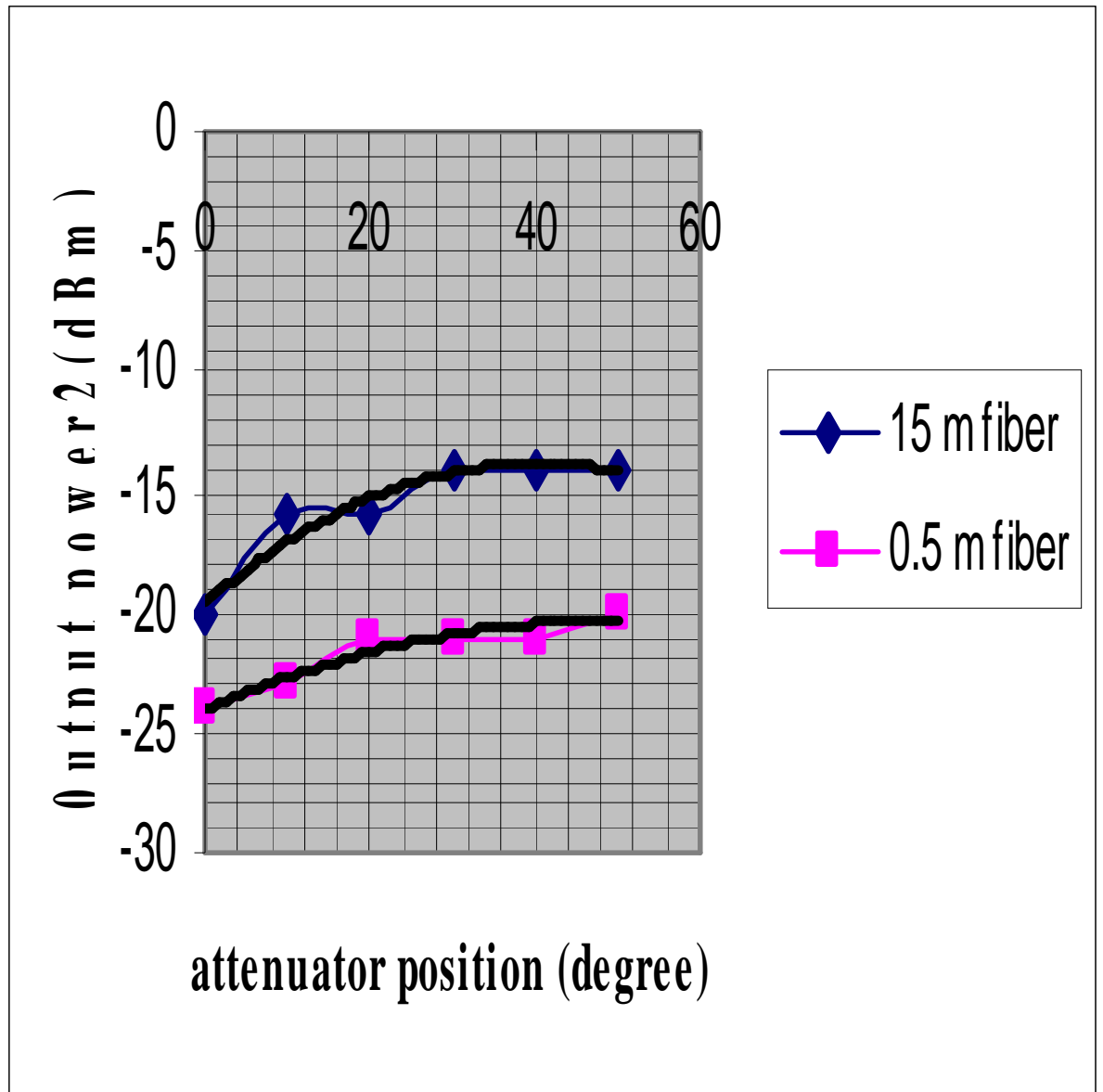


Figure 4.1 Microwave detector output power as a function of attenuator position degrees (experimented and fitted data).

The figure shows the relation between detected microwave output power and the attenuator position ( $\theta^\circ$ ) for 5 k pulse/sec transmitted frequency. The experiment is carried out using different transmitted RF output power (output power 1, output power 2) and two optical fiber lengths (0.5 and 15) m. It is clear that the relation between the RF output and attenuation value is exponential relation satisfying the theoretical relation.

## **Optical fiber system performance:**

### **Power budget:**

Given the required receiver power and available transmission power, the upper limit of the allowable loss from the transmitted power is called the power budget. If the transmission power is  $p_t$ , and the minimum required receiving power is  $p_{r\min}$  the power budget is:

$$\text{Power budget} = \frac{p_t}{p_{r\min}} \quad (4.1)$$

$$\text{Power budget [dB]} = p_t \text{dB} - p_{r\min} \text{dB} \quad (4.2)$$

### **Quantum efficiency ( $\eta$ ):**

The quantum efficiency  $\eta$  is defined as the fractions of incident photons, which is absorbed by the diode photodetectors and generate electrons which are collected at the detector output terminals. It's given by this simple equation:

$$\eta = \frac{\text{Number of electrons collected}}{\text{Number of incident photons}} \quad (4.3)$$

or

$$\eta = \frac{r_e}{r_p} \quad (4.4)$$

where  $r_e$  is the collected electron per second, and  $r_p$  is the incident photon per second.

### **Detector responsivity:**

The detector responsivity gives a measure of the detector sensitivity to radiant energy. It's the ratio of the detector

output to the light input. The responsivity  $R_\lambda$  is used to characterize the performance of a photodetector.

$$R_\lambda = I_p / p_o \quad (4.5)$$

where  $I_p$  is the output photocurrent in Amperes, and  $p_o$  is the incident optical power in Watts.

The relationship for responsivity may be developed to include quantum efficiency as follows. If the energy of a photon  $E = hf$ , and thus the incident photon rate is  $r_p$  may be written in terms of incident optical power and the photon energy as:

$$r_p = \frac{p_o}{hf} \quad (4.6)$$

The quantum efficiency  $\eta = r_e / r_p$

thus

$$r_e = \eta r_p$$

From equation (4.4) and (4.6) we obtain:



$$r_e = \frac{\eta P_o}{hf} \quad (4.7)$$

Then the output photocurrent is

$$I_p = \frac{\eta P_o e}{hf} \quad (4.8)$$

where  $e$  is charge of an electron. Thus responsivity may be written as:

$$R = \frac{\eta e}{hf} \quad (4.9)$$

The frequency  $f$  of the incident photons is related to their wavelength  $\lambda$  and the velocity of light in air  $c$  by:

$$f = \frac{c}{\lambda} \quad (4.10)$$

By substituting equation (4.10) into equation (4.9) the responsivity is given by:

$$R = \frac{\eta e \lambda}{hc} \quad (4.11)$$

And this is a useful relationship between responsivity and the wavelength of the incident light.

### **Transmission distance:**

The transmission distance is limited by:

$$L_{\max} = \frac{1}{\alpha_f} (10 \log_{10} P_t - 10 \log_{10} P_{r \min} - \text{other loss dB}) \quad (4.12)$$

where  $\alpha_f$  is the fiber attenuation in units of dB/km.

And the achievable transmission distance is essentially limited by  $p_t$  and  $p_{r \min}$ . The  $L_{\max}$  is the maximum distance that can be traveled by  $P_t$  and detected by  $P_{r \min}$  and the system becomes out of order when the distance exceeds this value.

## Detector sensitivity and the bit rate:

In communications the minimum required received power increase as the transmission bit rate increases. In most cases, they are linearly proportional. As the bit rate increases, the bandwidth of the signal increases. Therefore, the receiver needs to have a large bandwidth to receive the signal. Also as the receiver bandwidth increases, more noise power passes through. To maintain the same received signal to noise ratio (SNR), the signal power thus should also be increased.

The receiver sensitivity  $P_{r\min}$  is linearly proportional to the transmission bit rate:

$$P_{res.} = P_{r\min} \frac{V}{B_o} \quad (4.13)$$

$$P_{res}[dB] = P_{r\min}[dB] + 10 \log_{10} \left[ \frac{V}{B_o} \right] \quad (4.14)$$

where  $V$  is maximum bit rate, and  $P_{res}$  is the receiver sensitivity at bit rate  $B_o$ . Subtracting equations:

$$L_{MAX} = \frac{1}{\alpha_f} [(P_x - P_{res})dB - 10 \log_{10} \frac{V}{B_o} - otherloss]$$

(4.15)

$$= L_{MAX} .o - \frac{10}{\alpha_f} 10 \log_{10} [\frac{V}{B_o}]$$

(4.16)

### **Computing the signal to noise ratio:**

The signal to noise ratio (SNR) of the optical fiber photodiode receiver can be computed. The amount of the generated current in the photodiode  $I_p$  depends on the incident optical power on the photodiode in the optical link. The incident optical power on the photodiode detector is about  $9.6 \mu w$  or  $-20$  dBm and the responsivity of the used detector is  $0.5$  A/W, by substituting these values in the equation 4.5, the result can be obtained. The noise coming from the thermal noise current  $i_n$  generated from the load resistor  $R_L$  is:

$$i_n = \sqrt{\frac{4kT\Delta f}{R_L}} \quad (4.17)$$

where  $k$  is the Boltzmann's constant,  $T$  is temperature,  $\Delta f$  is the electrical signal band width, and  $R_L$  is the load resistor.

The noise current  $i_n$  can be calculated from the last equation. Then the S/N ratio can be obtained:

$$(S/N)_{dB} = 20 \log\left(\frac{I_p}{i_n}\right) \quad (4.18)$$

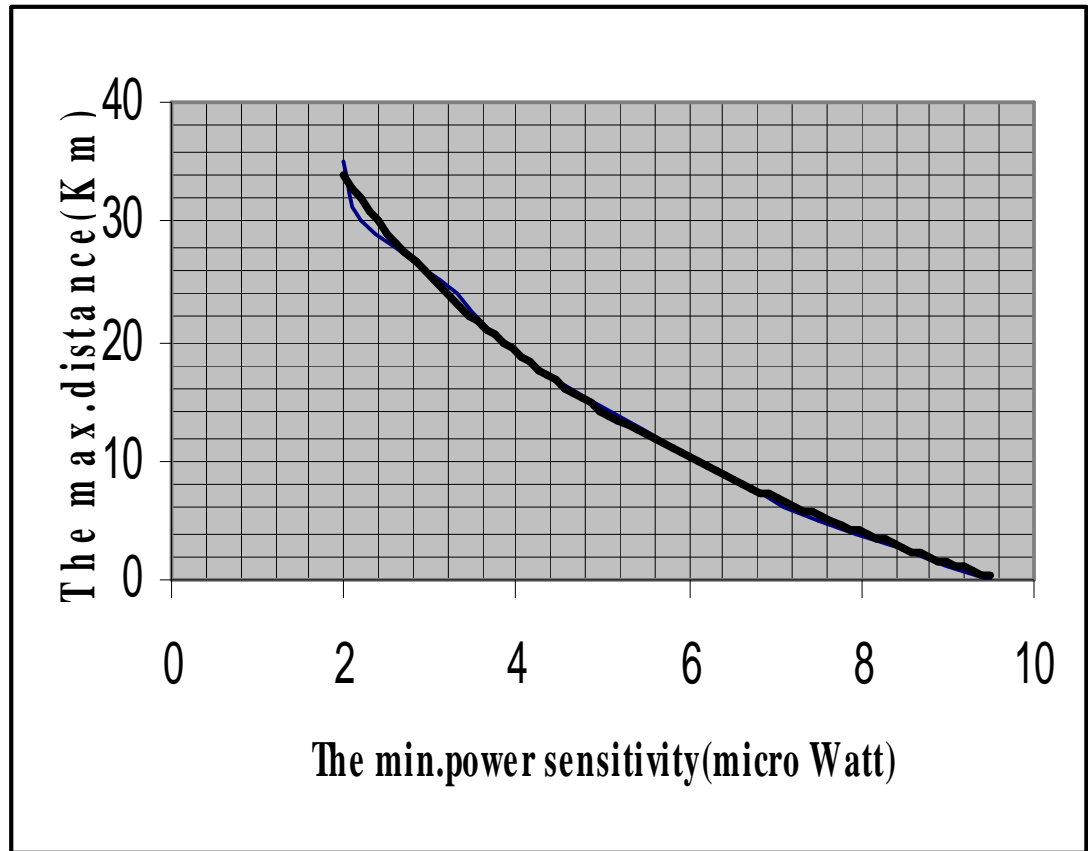


Figure 4.2 The relation between the maximum distance (Km) and the minimum power sensitivity( $\mu\text{W}$ ). (experimented and fitted data).

From the above figure it is clear that the maximum distance for the practical work that can be achieved about 30 km, but this distance can be reduced to equal 4 km when the minimum sensitivity increase to 8  $\mu\text{w}$ , at constant receiving power 9.6 $\mu\text{w}$  the result form this figure is that the maximum distance increased when the minimum power sensitivity decrease and the maximum distance decreased when the

minimum power increase. We expected a maximum distance in case of choosing another photodetector with smallest power sensitivity.

Figure 4.3 indicates the maximum bit rate that can be achieved at the maximum distance which was calculated using the practical results. Also it is clear that for the practical work the maximum distance can be achieved at 2 Mbit/sec. And the distance decrease until it reach to zero at bit rate equal about 6.4 Mbit/sec. That means the system become out of order at this bit rate and we must notice that this value was calculated for constant receiving power  $9.6 \mu\text{W}$  and minimum power sensitivity  $2.8 \mu\text{W}$  because we will study the effects of these parameters in the discussion.

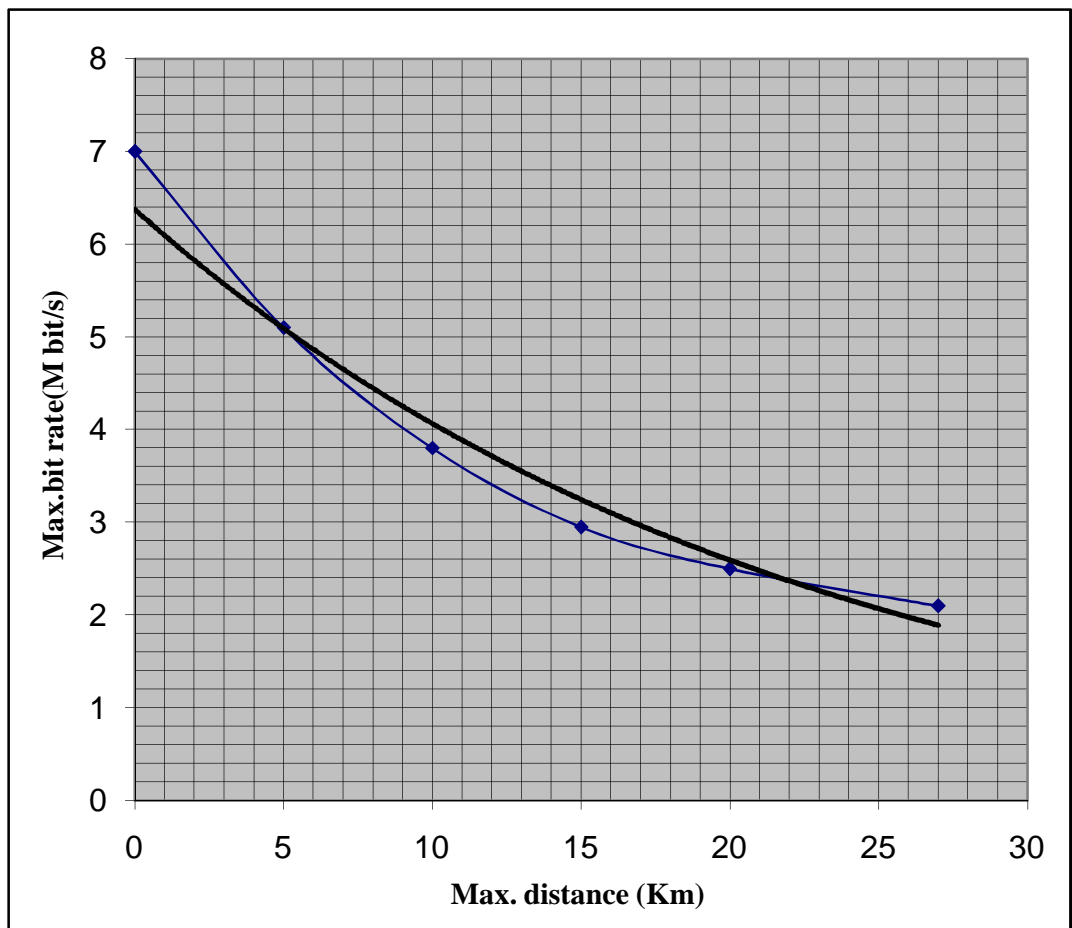


Figure 4.3 The relation between the maximum bit rate and the maximum distance (experimented and fitted data).

### **Discussion of the optical fiber system results:**

1. The receiver power should be larger than the receiver sensitivity to account for some additional receiver performance degradation due to intersymbol interference. Intersymbol interference is the pulse spreading phenomenon. It is reduce the power separation between received 1s and 0s. The effect of intersymbol interference on the bit error rate is equivalent to a loss of received power of a few dB.

In the practical a 4.9 dB excess power should be enough to compensate the loss due to intersymbol interference.

2. The maximum distance can be achieved by increasing the received power and decreasing the minimum power sensitivity that can be obtained by different methods such as:

(i) If there is no available optical source that can give receiving power greater than  $9.6\mu\text{W}$ , then we can choose photodetector with power sensitivity less than  $2.8\mu\text{W}$ , the maximum distance will be increase rapidly as shown in figure 4.4.



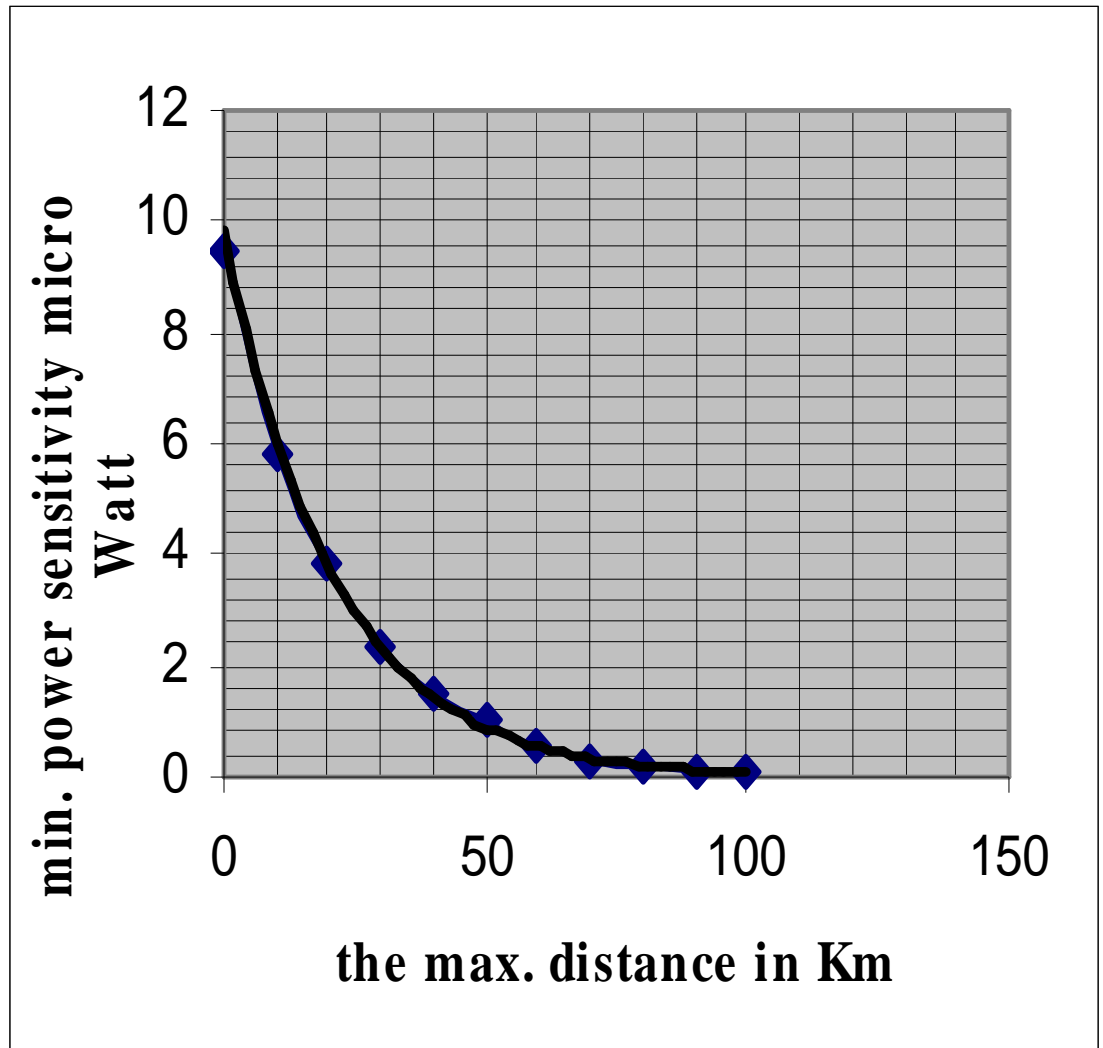


Figure 4.4 The minimum power sensitivity against the maximum distance (experimented and fitted data).

Figure 4.4 indicates that the maximum distance increased to about 90 Km where the photodetector power sensitivity is less than  $0.1 \mu\text{w}$

(ii) If there is no available photodetector that can receive power smaller than  $2.8 \mu\text{w}$ , then we can choose an optical source that can give more than  $9.6 \mu\text{w}$ , the maximum distance will be increased rapidly as shown in figure 4.5

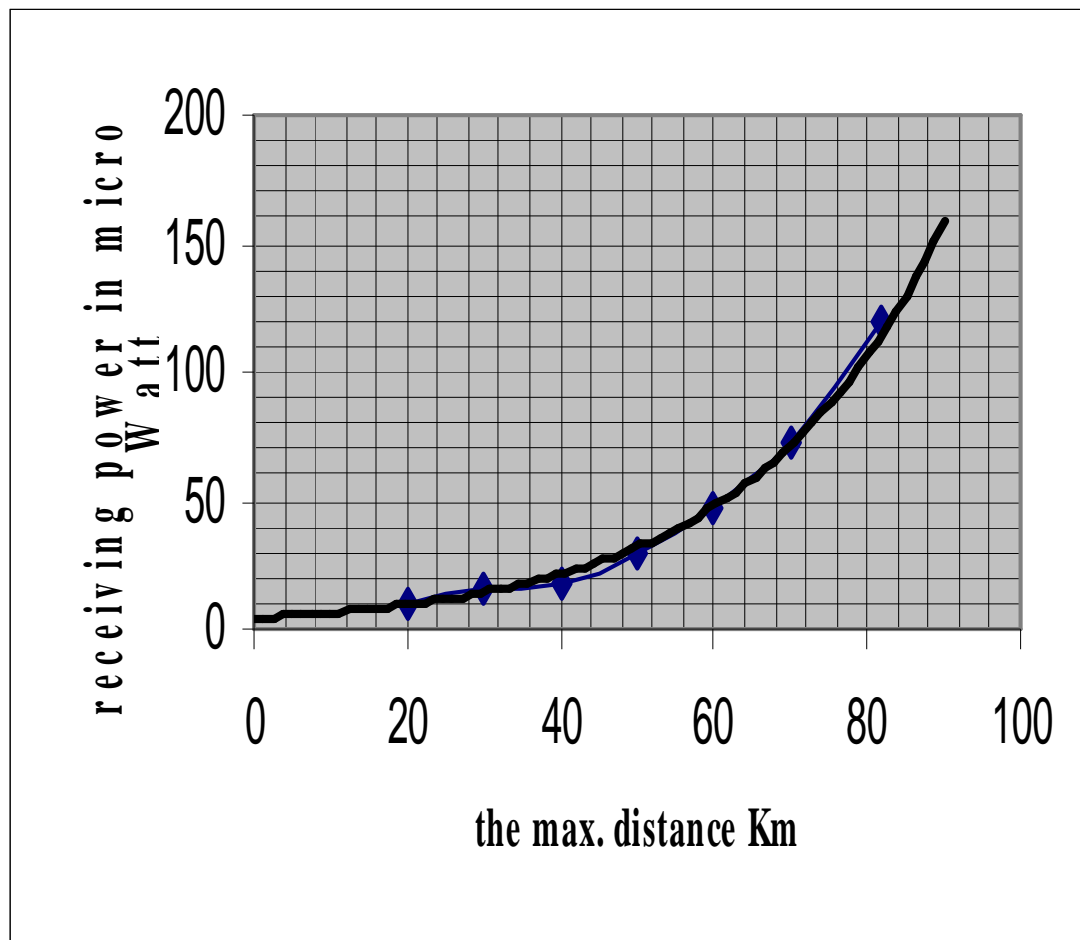


Figure 4.5 The received optical power against the maximum distance (experimented and fitted data).

The maximum distance in figure 4.5 is achievable up to 82 km if the receiving power reaches to  $120 \mu\text{w}$ .

(iii) By increasing the receiving power and decreasing the minimum power sensitivity, the maximum distance is then expressed in terms of the power budget, where the power budget is the difference between the receiving power and minimum power sensitivity as shown in figure 4.6.

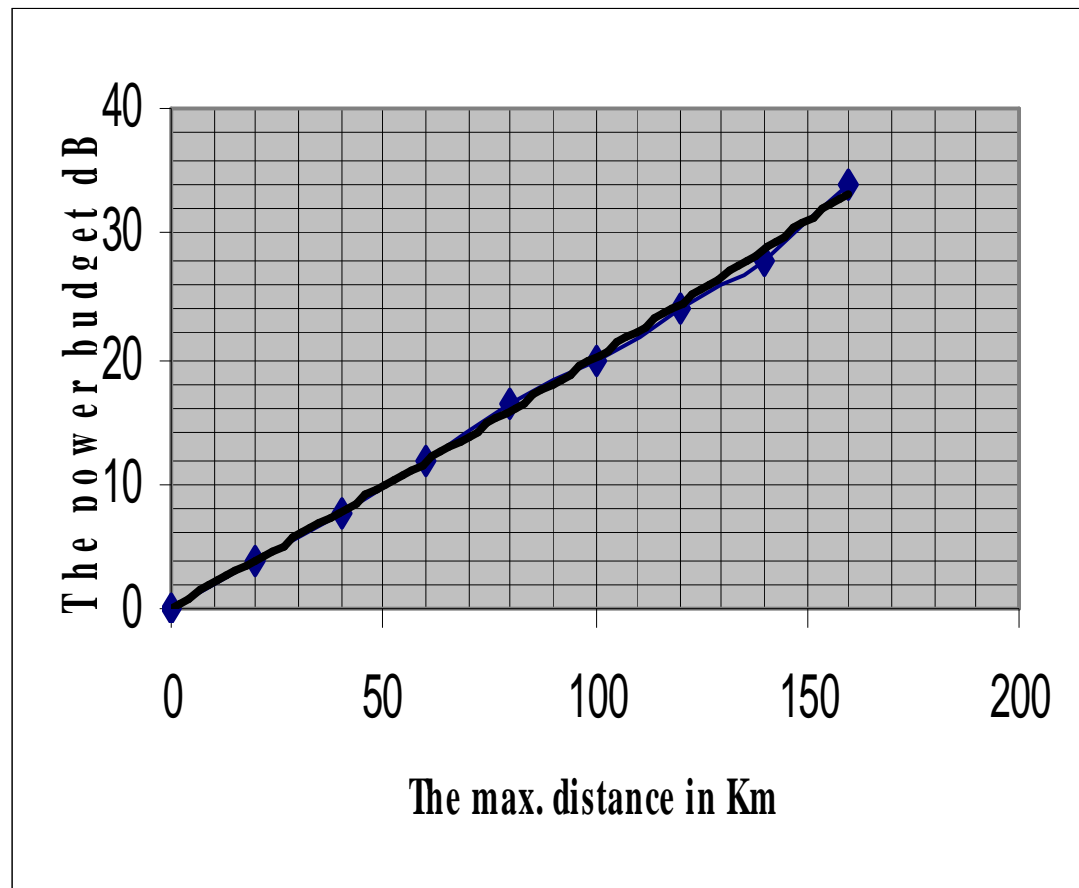


Figure 4.6 The relation between the power budget and the maximum distance. (experimented and fitted data).

From figure 4.6 the maximum distance is achieved as the power sensitivity decreases to  $0.1 \mu\text{w}$  and the receiving power increase to  $120 \mu\text{w}$  at 155 km.

3. The power sensitivity and the receiving power have the same effects on the maximum bit rate. This can be explained as follows:-

(i ) For constant power sensitivity, the maximum bit rate increase when ever the receiving power increase as shown in figure 4.7 This relation shows a linear behavior.

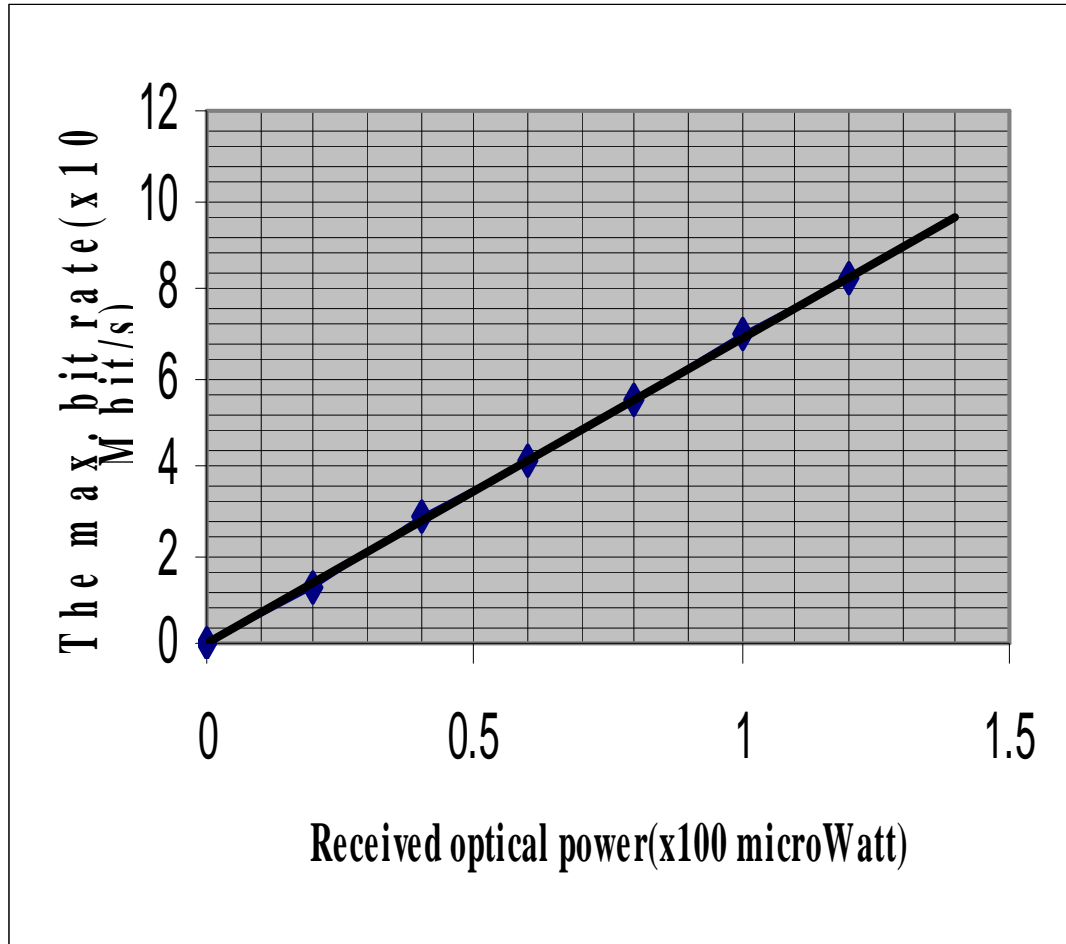


Figure 4.7 The maximum bit rate against received optical power (experimented and fitted data).

In figure 4.7, the maximum bit rate exceed 80 Mbit/s when the receiving power reaches to 120  $\mu\text{w}$ , this value of maximum bit rate was calculated at constant power sensitivity.

(ii) The maximum bit rate increase with the power sensitivity at the constant receiving power, finally the bit error rate can

be increased with increasing the receiving power and decreasing the power sensitivity as shown in figure 4.8.

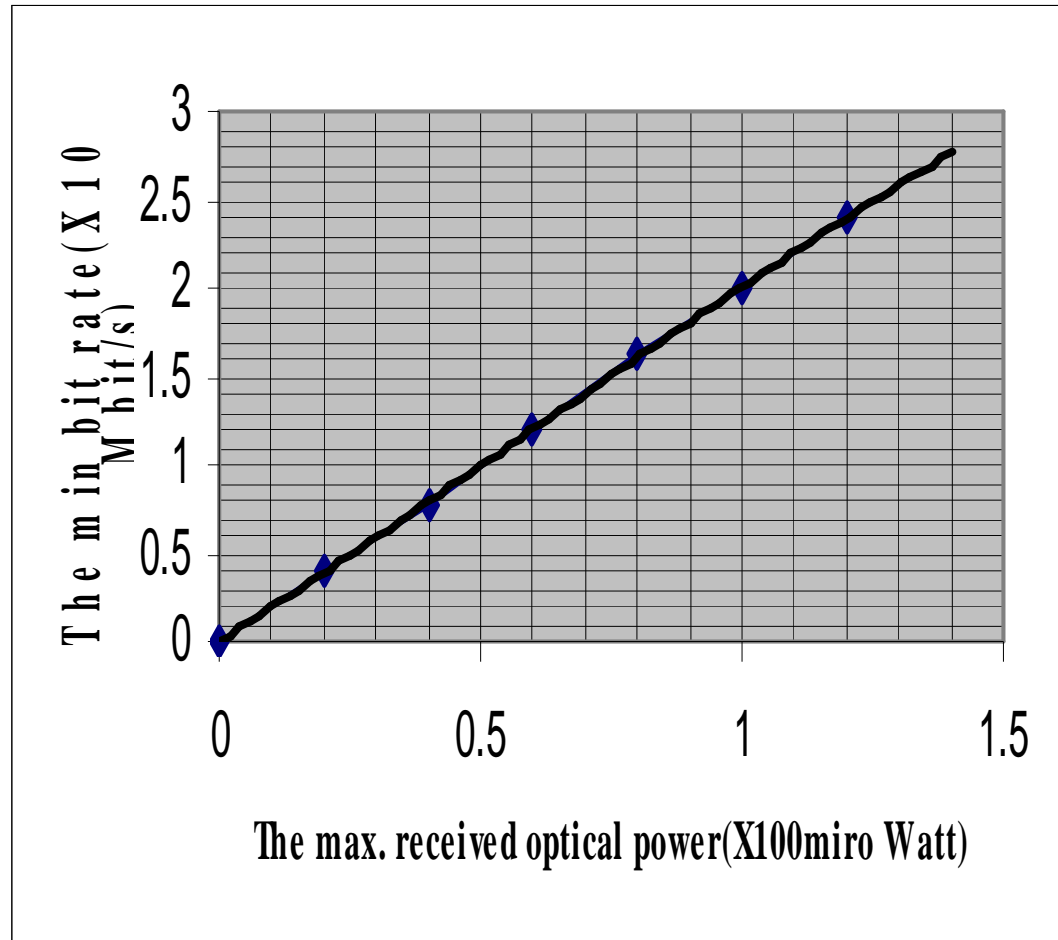


Figure 4.8 The maximum bit rate versus the maximum receiving power (experimented and fitted data).

Figure 4.8 was plotted in terms of the receiving power and it can be plotted in terms of the power budget.

### **Antenna remoting RF optical fiber system performance:**

For all applications, the noise, linearity, and gain stability meet the requirements for use in an antenna

remoting system. In RF optical link, the main transmitted and receiver signal between the control room and the antenna site should be carried. This link should be allowed the continuous monitoring of composite up link signal at the output of the antenna site.

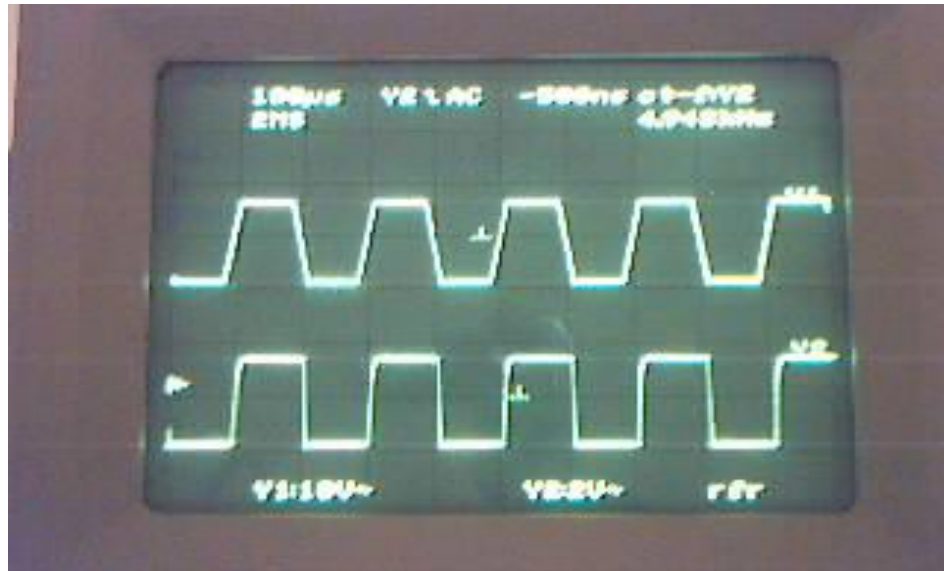


Figure 4.9 Represents the input RF signal and received optical output signal (min. power, 0.5 m fiber)

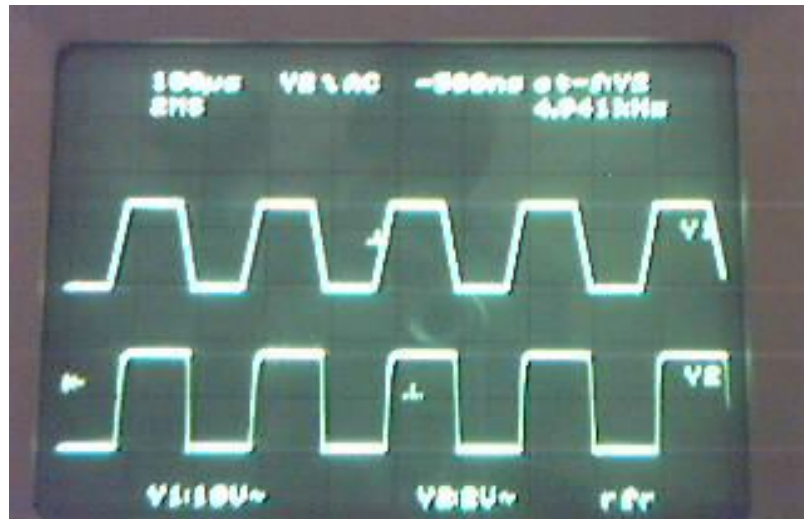


Figure 4.10 Represents the input RF signal and received optical output signal (min. power, 15 m fiber)

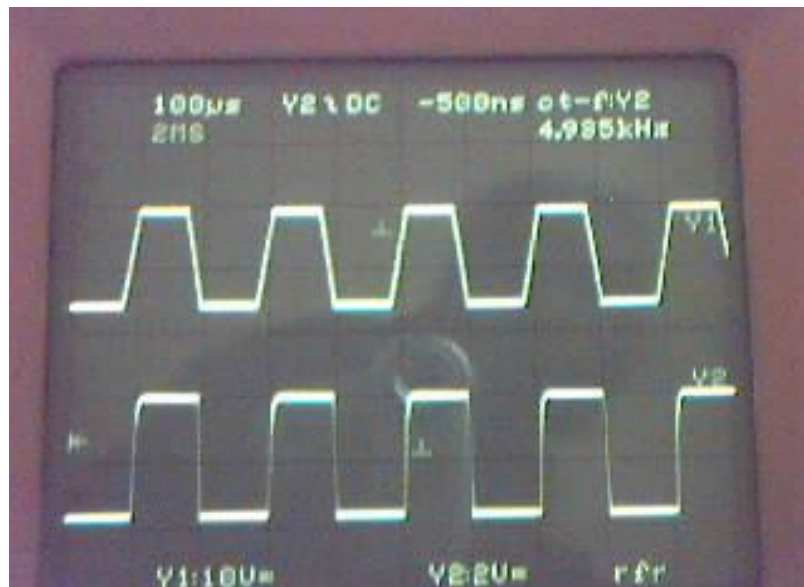


Figure 4.11 Represents the input RF signal and received optical output signal (max. power, 0.5 m fiber)



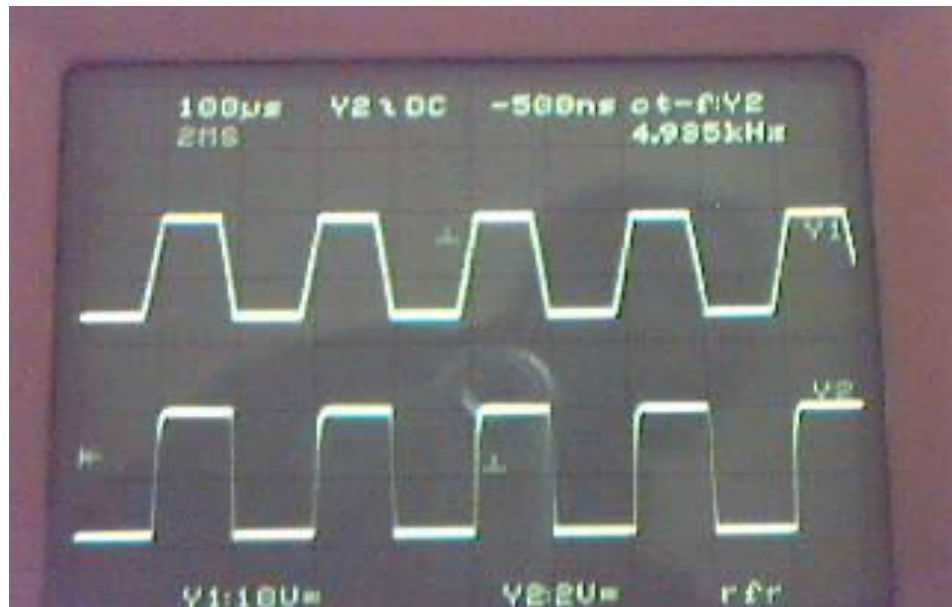


Figure 4.12 Represents the input RF signal and received optical output signal (max. power, 15 m fiber)

It is clear from these figures the input RF signal is similar to the detected amplified optical signal. The figures show the good achieving work for detection and amplification processes.

When the transmitted RF power is attenuated by the position angle of the flap attenuator, the detected output signal level is decreased also. This means that the optical part has a good linearity. It means it is suitable to achieve the goal of the present work.

## **Conclusions:**

Many points can be summarized the performance of the RF and optical systems, as follows:

1. The use of fiber optics allows the remote microwave link to be constructed that very low propagation loss and dispersion and have a high degree of immunity from external effects.
2. RF fiber optic links are rapidly becoming feasible for use in radar systems with significant improvements in weight, size, flexibility and electromagnetic interference (EMI) immunity.
3. This system can be used in different fields like in aircraft of the future with significant impacts on their design.
4. The successful RF optical fiber communication system depends on the maximum distance, and the maximum bit rate that can be transmitted by optical transmitter and detected by optical receiver.
5. Link was been demonstrated with reasonable performance to X- band RF (10.687 GHz) with both wideband and narrow band transmission characteristics.

6. The received microwave signal must be amplified before it enters the laser diode driver to ensure that no mismatching case occurs.

7. The lowest attenuation is achieved at frequency equal 4.5 KHz.

8. Because the suitable low attenuation of optical fiber for optical signal at 5 KHz, the optical signal can travel into a long distance before it is converted into electrical signal using the photodetector.

## **Suggested future work:**

- Interfacing the whole system with a PC to better data processing and decision making.
- Extending the work in the direction of image processing to enhance the detected target image.
- Finally rechange multi-target detection to simulate real radar system.

