A Multi-wavelength Erbium Doped Fiber Laser for Free Space Optical Communication link

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Abstract- In terrestrial optical communications, optical fiber transmission links are vital for both short and long distances networks. This is due to their high bandwidth capability that translates into high speed data transmission. However, trench digging to lay the optical fiber cables makes their installation intricate and time consuming compared to optical wireless transmission. Meanwhile, Free Space Optical communication (FSO) links often employed in short distance, line of sight optical wireless transmission present competitive data rates if their bandwidth is maximized. We have considered using the Wavelength Division Multiplexing (WDM) technique in the development of a FSO link prototype to increase the capacity of the link. Currently, most FSO links use single wavelength Laser Diodes (LD) in their transmitters. We propose the design of a multi-wavelength Erbium doped fiber laser (EDFL) source, to avoid the use of multiple LD in the prototype. In this paper, an EDFL source with emission wavelengths at 1540nm, 1547nm and 1555nm is presented. Characteristics of the Laser source such as output optical power and laser wavelengths are controlled by optimizing the laser parameters such as length of the gain medium, coupling ratio of the output mirrors and the laser pump power.

Index Terms—WDM, multi-wavelength Erbium Doped fiber laser.

I. INTRODUCTION

Free Space Optical (FSO) communications is a point-to-point transmission of communication information (data, video and voice) through the atmosphere using the laser light as the optical carrier signal. In recent years, FSO communication has received considerable attention as an alternative to existing fiber and RF communication systems [1]. Such attention is due to the lower cost and easier installation of FSO links compared to fiber optic systems. This is because of the nonexistence of the requirements to dig and lay the optical cables underground. Moreover, some other advantages of FSO with respect to radio frequency links, such as no spectrum license requirement and immunity to interference have made FSO particularly unique system for broadband wireless communication as Last mile access technology[2],[3].

Atmospheric conditions, such as fog, rain, wind, snow, and clouds are potential challenges for FSO links [4]. These weather conditions have attenuation effects that cause detrimental fluctuations in the intensity of the received optical signal, resulting in the link impairment. When they occur in their severity, these weather conditions, exhibit attenuation coefficients of over 100dB/km [5]. However, FSO field researchers have proposed techniques of mitigating the atmospheric related attenuation such as the application of Multiple Laser Multiple Detector (MLMD) technique [6-7]. In this approach, data transmission is achieved by using multiple laser beams that are propagated simultaneously to a receiver with multiple apertures of separate detectors. Multiple-Laser-Single Detector (MLSD) has been used in [8], where multiple laser beams are transmitted to a receiver with single aperture. Additionally, FSO communication link operation depends on the line-of-sight between the transceivers of the link [1]. The transceivers at both link ends must be properly aligned for optimum operation. If alignment is not properly achieved, it could results in a FSO link communication failure. The basic block diagram of the FSO link is shown on figure 1. The transceiver on building 1 is in line-of-site with the transceiver on building 2.

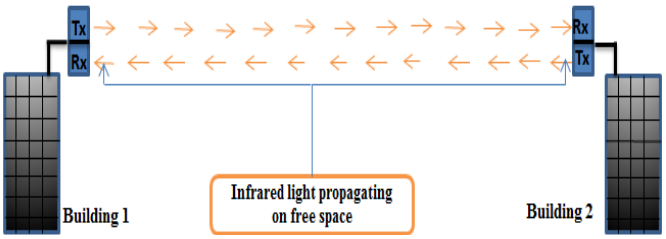

Figure 1- Illustration of a basic FSO link forming a connection of networks situated in two separate buildings.

Traditionally, FSO links transmit information by employing single wavelength Laser Diodes (LD) optical sources with wavelengths of 780nm or 850nm [1]. The transmission rates of 1Mbps up to 2.5 Gbps and operating range of 4.4km are reported [9]. The bandwidth enhancement above the available data rates remains a challenge since FSO links use single wavelength optical sources. Additionally, a FSO user needs to implement additional links which result in an increased cost of the link. However, by the application of a Wavelength Division and multiplexing (WDM) technique, the capacity of a FSO shall be increased. WDM technique is the transmission of data through modulation and multiplexing of a multi-wavelength optical carrier. WDM technique is implemented by using optical sources of different wavelengths.

We propose the development of a multi-wavelength laser source for the implementation of a WDM technique. This laser source is based on the Erbium Doped fiber laser (EDFL). The EDFL is a laser in which the active gain medium is an optical fiber doped with rare-earth element, Erbium [10]. Multi-wavelength Erbium doped fiber lasers have their potential applications in optical communications, optical fiber sensors and spectroscopy [11].

The block diagram of the proposed FSO link transmitter and the receiver is shown in figure 2, where the laser source is a multi-wavelength Erbium doped fiber laser.

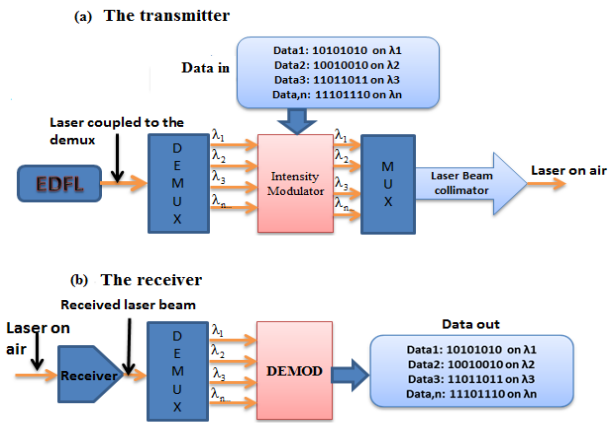

Figure 2- Block diagram of the proposed multi-channel FSO link (a) the transmitter and (b) the receiver

The EDFL source generates the multi-wavelengths light signal. The de-multiplexer separates the wavelengths of the light source. The optical intensity of each of the optical signals is modulated by data signals through the use of the intensity modulators. The modulated optical signals are multiplexed into a single optical signal and transmitted to the receiver via atmospheric channel through the laser beam collimator. The received optical signal is then de-multiplexed into different wavelengths. The wavelengths carrying the data are demodulated and the data is recovered. The development of the multi-wavelength EDFL source is crucial because it provides the multi-wavelength signal that enables the application of a WDM transmission. The laser source shall be used in the FSO link prototype. Therefore in this paper, the focus is on developing this laser source.

II. BASIC THEORY OF ERBIUM-DOPED FIBER LASERS

Similar to other laser operation, three processes take place for an EDFL to operate: stimulated Absorption, Spontaneous emission and Stimulated emission. Additionally, there is a process called population inversion. Population inversion occurs when the majority of Erbium ions in the ground state have elevated to the metastable level, figure 3.

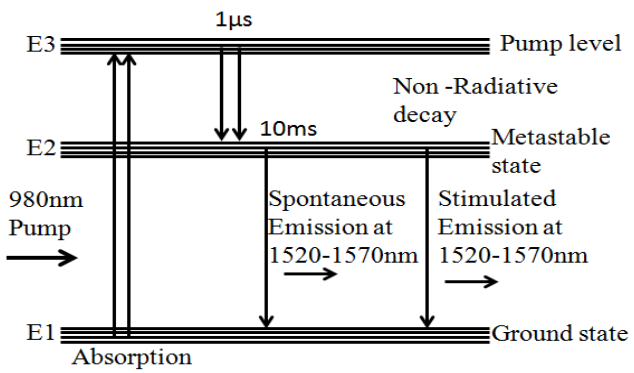

Figure 3- Three level energy diagram of Erbium ions in Erbium doped fiber [13].

When the pump light is launched into the Erbium doped fiber, the photons of the pump radiation that have the energy similar to the energy deference between energy level 3 and energy level 1(figure 3, E3 and E1 respectively) are absorbed by the Erbium ions on their ground state E1. This is called stimulated absorption. The Erbium ions gain energy to move to Energy level 3(pump level). Due to the very short life time (typically 1µs) of ions in the pump level, they decay to energy level 2 (figure 3. E2, metastable state) without any radiation (Non- radiative decay). In the metastable level, the ions can stay for a period of approximately 10ms before they decay to their original ground state [13]. When the ions decay to their ground state after 10ms, they release energy in the form of photons with wavelengths ranging between 1520- 1570nm. This is termed as spontaneous emission. The spontaneously emitted photons differ in their relative phase, frequency and propagation direction [13]. The ions can be made to decay as early as before the end of their life time in the metastable level. This process also releases photons with wavelengths in the range of 1520-1570nm and is called stimulated **emission.** Stimulated emission is achieved when incident photons with characteristic wavelengths in the range of 1520-1570nm interact with excited ions in the metastable level. This results in the emission of photons that are duplicate of the incident photons with similar characteristic frequency, phase and propagation direction. Therefore, the requirement in a laser is to make the stimulated emission a dominant process over spontaneous emission. This is achieved by creating a feedback optical path at the output of the doped fiber through which the spontaneously emitted light is propagated to the Erbium doped fiber input to interact with excited ions and cause stimulated emission.

A. Basic configuration of an Erbium Doped fiber laser

In its simplest configuration, an Erbium-doped fiber laser consists of a pump source, a laser cavity and a gain medium as shown on figure 4. The pump source is a semiconductor laser diode, typically 980nm wavelength. The fiber laser cavity is accomplished by the two mirrors at the fiber ends, M1 and M2. The amplifying medium comprises the Erbium doped fiber (EDF).

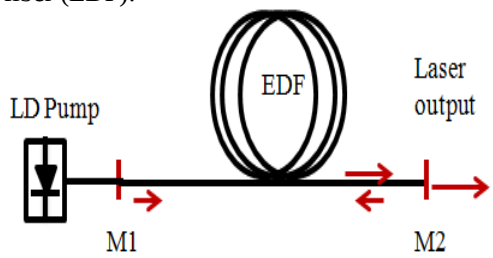

Figure 4 - Linear cavity EDFL diagram

The pump source injects light into the doped fiber through a wavelength depended reflector mirror M1. The wavelength dependent reflector mirror is totally transparent to the pump wavelength and totally reflective to the light generated in the EDF. The pump light is absorbed in the EDF to excite Erbium ions to move from their lower energy state (ground state) to their higher energy state metastable state to generate spontaneous emission. The output reflector mirror M2 completes the laser cavity and forms the output coupler for the laser light. This mirror must be partially reflective so

that it reflects a percentage spontaneous emission back to the amplifying medium to maintain laser oscillation and transmit a percentage of the light as a laser output. The doped fiber is chosen on the basis of specific laser characteristics such as the emission wavelength range. Erbium doped fiber, is applied in the case of Erbium doped fiber laser, where the lasing wavelength is within the range of the telecommunication window (1520nm-1570nm). The telecommunication window is the range of light wavelengths that correspond to the lowest attenuation in the standard telecommunication optical fiber. The basic fiber laser on figure 4 is termed a linear cavity laser. Its main advantages are its simplicity and the possibility to make very short cavities [12]. This type of fiber laser configuration has a disadvantage of the spatial hole burning which results from the standing wave pattern formed by the signal traveling from the EDF to the output of the laser and the reflected signal from the output coupler M2 [12]. This causes the output power of the laser to reduce. The other fiber laser configuration is a ring cavity laser and is shown in figure (5 and 7) in the next section, where the Experimental work and more details are presented.

III. EXPERIMENTS

There are two important characteristics that need to be taken into consideration when we develop the multi-wavelength EDFL for FSO link. The emission wavelengths and the laser output power. We have obtained an EDFL that is lasing at different wavelengths. This ensures the possibility of the implementation of the WDM technique in the multi-channel FSO link prototype and an optical output power in the milliwatt range power level. This determines the operation distance of the FSO link prototype as the FSO link range is a function of the transmitter optical power.

A. Experimental setup of the proposed EDFL

The aim is to develop a multi-wavelength Erbium doped fiber laser. The multi-wavelength operation of this EDFL is based on the spontaneous emission of the EDF, which is reflected by the output mirrors of the laser. The output mirrors of the laser are achieved by Fiber Bragg Gratings (FBG1, FBG2, FBG3), figure 6. Fiber Bragg gratings are type of reflectors constructed in a segment of optical fiber that reflects particular wavelength of light and transmit all others. The wavelength of the light that is reflected by the Bragg gratings is Bragg wavelength described by equation 1 [15].

$$\lambda_{Bragg} = 2n_e\Lambda, \qquad (1)$$

Where n_e, is the effective refractive index of the grating in the fiber core and Λ is the grating period.

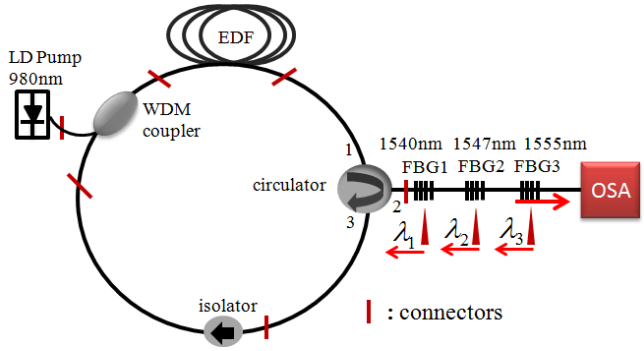

Figure 5- The experimental setup of the proposed multi-wavelength EDFL fiber laser.

The pump source is coupled to the EDF through the WDM coupler and provides energy to the system. The Erbium ions absorb this energy and get excited to the pump level of their energy state. They generate a broadband spontaneous emission with radiation ranging between (1525-1570nm). The broadband spontaneous emission propagates through the system to the optical circulator port 1. The circulator routes the signal to the output through port 2. The Bragg gratings FBG1, FBG2 and FBG3 reflect 10 % of the 1540 nm, 1547 nm and 1555 nm light of the broadband spontaneous emission and transmit the rest of the radiation as laser output. The optical spectrum analyzer (OSA) is used to monitor the laser performance.

The reflected light propagates to port 3 of the circulator. From port 3 of the circulator the light is coupled through the WDM coupler to the gain medium of the laser. The feedback signals generate stimulated emission of the 1540nm, 1547nm and 1555nm wavelengths. This way, the dominant oscillation of these wavelengths is created, resulting in a three wavelength emission laser operation, hence a multi-wavelength Erbium doped fiber laser, as seen on figure 6 below.

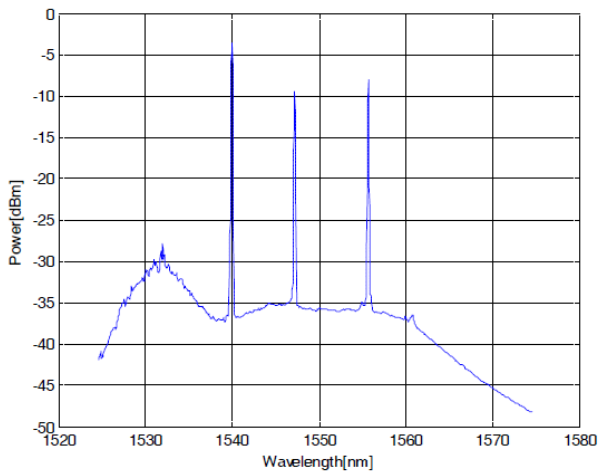

Figure 6- The laser power spectrum of a three wavelength EDFL

With this configuration we can print other Bragg gratings of different Bragg wavelengths. Thus, we can obtain a laser emission at more than three wavelengths. The Bragg wavelengths must be within the broadband gain profile of the Erbium Doped fiber Amplifier (1526-1570nm).

B. *The coupling ratio determination*

The purpose of this experiment is to determine the optimal coupling ratio of the laser output mirrors. The output coupling ratio determines the amount of optical power given out as a laser output and the power to be a feedback radiation for stimulated emission. The output coupling ratio is kept as a percentage value. Therefore 10% output coupling ratio means 10% of the power that is in the ring cavity is an output and 90% is feedback to the EDF.

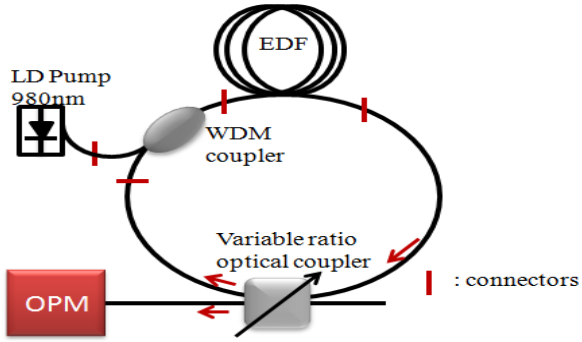

Figure 7 -The experimental setup for the determination of the output coupling ratio.

The pump source with 980nm wavelength and a 100mW optical power provides energy to the Erbium doped fiber (EDF) through the WDM coupler; the Erbium ions in the EDF absorb the pump energy and generate the broadband spontaneous emission. The spontaneous emission propagates to the variable ratio coupler. Determined by the coupling ratio, specific amount of power is a laser output power and laser feedback power. The variable coupler provides the feedback and output power of the laser. The spontaneous emission that is coupled back to the EDF through the WDM coupler causes the stimulated emission. By varying the coupling ratio and monitoring the evolution of the output power, we determine the optimal coupling ratio for the Erbium doped fiber laser. The results are shown below.

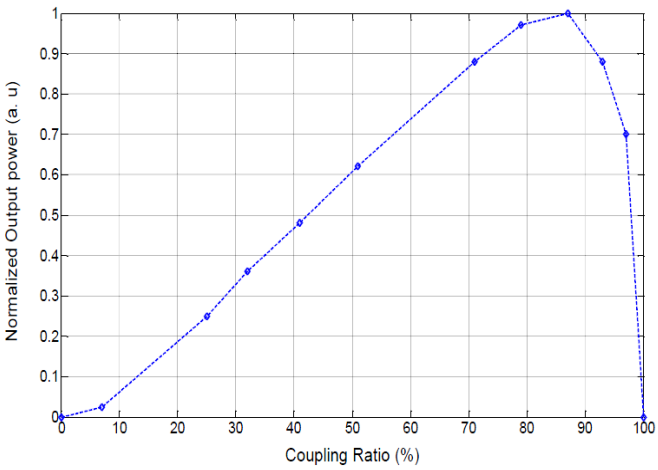

Figure 8- The effect of the output coupling ratio on the output power of the EDFL

From the graph, it is observed that the maximum output power of the laser is obtained at an output coupling of 87% where 87% (approximately 90%) of the ring cavity light is an output and 13% is a feedback to the ring cavity. This is an optimum coupling ratio in this EDFL. The output mirror need to be approximately 10% reflective and 90% transparent to the EDFL signal power. When the coupling ratio is more than 96%, it is observed that the laser power has decreased. This means that there is no sufficient power to feedback to the EDF to maintain oscillation.

C. *The effect of the pump power on the output laser power*

In this experiment, we evaluate the effect of the pump power on the output power of the EDF ring laser shown on figure 7. The purpose of this experiment is to determine the optimal pumping power when the 3.5m of the low concentration Erbium doped fiber is used as a gain medium. The output coupling ratio is 90%. The results of this experiment are shown on figure 9 below. The pump power was varied from (0-110mW).

From the graph it is seen that the output power of the lasing wavelengths grows linearly with the increase in the pump power. The linearity starts to take place at approximately 13mW, 20mW and 26mW for 1540nm, 1555nm, and 1547nm respective lasing wavelengths. These pump powers are termed threshold pumper powers for the three wavelengths of the ring laser cavity EDFL.

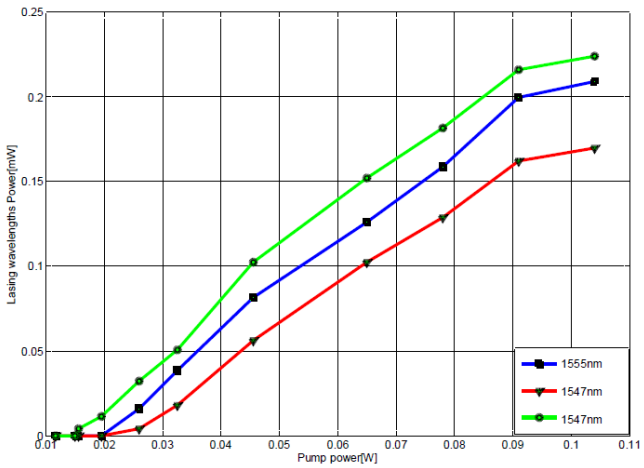

Figure 9- The dependency of the laser output power on the pump power.

The output power reaches the highest power when the pump power is at 110mW. This is a point where the EDF is fully inverted and exhibits the maximum gain to lasing wavelengths optical power. Therefore in our configuration of the multi-wavelength laser, this is the technique we used to obtain an optimal pump power for the laser.

IV. DISCUSSION AND FUTURE WORK

The gain spectrum of the EDF is a broadband signal covering the 1525-1570nm wavelength region. However, the gain is non-uniform throughout the spectrum. The spectrum has a narrow high gain peak around 1532nm and a wide, non-uniform, gain peak from 1540nm-1570nm. This causes the output channels of different wavelengths of the laser to be different in power levels. This is because they are amplified by different gain levels. As can be seen on figure 6, the laser channel at 1555nm has higher peak power than the laser channel at 1547nm wavelength. This is not

supposed to happen because the gain at 1547nm is higher than at 1555nm. The reason for this is the output coupling ratio of the output mirror at 1555nm is less than 90% which means that the 1555nm grating reflectivity is more than 10% and reflects more power to cause stimulated emission. The same phenomenon applies for the channel at 1540nm, where the reflectivity of the grating is also more than 10%.

The results show that the optical output power level is low. This is due to the losses that occur as a result of connectors used in the system. With low optical power levels, the link range of the FSO link prototype will be limited to very short distances. However, in future, by using fusion splices instead of connectors, losses will be minimized and power levels will be improved. The other way of improving the power levels is the application of the post optical amplifier, where the optical power can be boosted before transmitted to the receiver of the FSO link.

V. CONCLUSION

We have demonstrated a multi-wavelength Erbium doped fiber laser, emitting at 1540nm, 1547nm and 1555nm wavelengths. Using the variable ratio optical coupler, we demonstrated the optimal coupling ratio of the output mirrors of the laser. The optimal pump power of the laser was determined by varying the pump power from zero to 110mW for the optimal coupling ratio. This multi-wavelength Erbium doped fiber laser shall be used in accomplishment of wavelength division and multiplexing in the transceivers of the FSO link prototype implementation.

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