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Research Article

Enhancement of Optical Amplification in Photonic Crystal Fiber Injected with Olive Oil

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Abstract

In this work, the liquid photonic crystal (olive oil) was injected in fiber to enhance the optical amplification of light according to Raman amplification technique. In this work it was used three types of fibers (LMA, ESM and Hollow core) fibers. The gain has been calculated for the three type of fibers (LMA, ESM and Hollow Core) fibers as (19.46 dB, 8.473 dB and 0.325 dB) respectively, also, the noise of these three type of fibers has been calculated as (-17.71 dB, -8.026 dB and 24.72 dB) respectively. Then, it was compared among these three types of fiber.

Keywords: *Raman amplification, liquid photonic crystal ,LMA fibers, ESM fibers, Hollow Core fibers, olive oil, Photonic Crystal Fiber, Raman Gain, erbium-doped fiber, Noise Figure.*

1. Introduction

Raman Fiber amplifiers (RFAs) are obligatory components of long-haul fiber-optical systems in modern telecommunications with terabit information exchange rates. In fact, due to their implicit advantages RFAs have edged legacy erbium-doped fiber amplifiers (EDFA) out of these systems (A. J. L. Gimlet *et al*., 1990). Just RFAs give the unprecedented possibility of practical familiarization with the total telecommunication S+C+L frequency window (with broadening the channel information volume up to more than 20 THz) (B. P. B. Hansen, *et al*, 1998). Nevertheless, the simplicity of RFAs realization is accompanied by a huge intricacy of nonlinear processes of energy interchange between several pump waves and hundreds of signal waves in stimulated Raman scattering (SRS), which strongly complicates the synthesis of these amplifiers (C. Mohammed N. Islam *et al*, 2002).

The advantages of fiber Raman amplifiers over the optical amplifiers include the possibility to operate in any wavelength region and superior noise performance of distributed amplification, as well as permits, with the appropriate choice of pump wavelengths and powers, flattening of the gain profile over the whole bandwidth (D. J.K. Behera *et al)*.

Raman fiber amplifiers (RFAs) have low gains per unit length compared with erbium-doped fiber amplifiers (EDFAs) and semiconductor optical amplifiers (SOAs) (E. Urquhart P *et al*, 2007). Therefore long optical fiber spans are required to provide useful performance. The RFA guides light at both the signal and pump wavelengths and it is normally single mode to ensure the best overlap of all traveling waves. Highest gains are achieved by using fibers with small effective areas and low losses (F. Mandelbaum I *et al*, 2003).

One of the great benefits of RFAs is that they do not require special dopants. The optical fiber can be one of the common types used for transmission or dispersion compensation. Moreover, as the spectral shape of the Raman gain depends primarily on the frequency separation between pump and signal (not their absolute frequencies) (G. Bromage J., 2004).

2. Theory

2.1 Raman Gain

In a simple approach, valid under CW or quasi-CW conditions, the initial growth of the Stokes wave can be described by equation (1), where I_S Is the Stokes intensity, I_P is the pump intensity, and z is the axis associated to the length of the fiber (H. Roger H. Stolen *et al*, 2002).

$$dI_s/dz = g_R I_p I_s \tag{1}$$

The propagation equations are obtained directly from (1), and are described by (2) and (3), for the signal and pump respectively. In (2), (3), A_{eff} represents the effective core area; P_S and P_P are the power of signal and pump respectively, with frequencies ω_S and ω_P, and attenuations in fiber α_S and α_P for signal and pump respectively (I. Swami Srinivasan, February, 2002).

$$dP_s/dz = -\alpha_s P_s + (g_R/A_{eff}) P_s P_p \tag{2}$$

$$dP_p/dz = -\alpha_p P_p - (\omega_p/\omega_s)(g_R/A_{eff}) P_s P_p \tag{3}$$

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The second term in the right side of (3) is responsible for pump depletion, if we neglect it and solve the equation and substitute in (2) we obtain (4), where P_{PO} is the pump power at z=0 (J. A. Teixeira *et al*, 2002).

$$dP_s/dz=-\alpha_s P_s+(g_R/A_{eff})(P_{po}\, exp(-\alpha_p z)\, P_s) \quad (4)$$

Raman gain coefficient, and polarization factor between the pump and signal light, respectively. From the two coupled Raman amplifier equations (3 and 4), the signal power of an amplifier of length L is:

$$P_S(L)=P_S(0)\exp\left(g_R\frac{P_0}{A_{eff}}L_{eff}-\alpha_S L\right) \quad (5)$$

where p_0 is the input pump power, L is the fiber length, and L_{eff} is the effective fiber length which can be defined as:

$$L_{eff}=\frac{1-\exp(-\alpha_P L)}{\alpha_P} \quad (6)$$

For short lengths, the effective length approximates L, and for long length, it reaches$1/\alpha_P$. Clearly, high Raman gain can be achieved with high pump power, long effective lengths, small effective area, high stimulated Raman scattering gain coefficients as well as low signal and pump attenuations (K. D. B. M. Pereira *et al*, 2003). Similarly, the resolution of (4) for z=L results in equation (5) that mentioned before.

Gain in Raman Amplifier is defined as the ratio between the output signal power with the pump on over the output signal power with pump off, then from (5) and (2) considering P_P=0, the non-saturated gain is given by (7) (J. A. Teixeira *et al*, 2002).

$$G=4.343[g_R L_{eff} P_0/K_p A_{eff} - \alpha_s L] \quad (8)$$

2.2 Noise Figure

The RA has essentially four sources of noise that contribute to degrade the NF, they are:

- Double Rayleigh scattering (DRS)
- Short Upper-state Lifetime (SUL)
- Amplified Spontaneous Emission (ASE)
- Temperature Phonon Stimulation (TPS)

Rayleigh scattering is due to the microscopic glass composition non-uniformity, which imposes several limitations in systems with optical amplifiers. DRS correspond to two scattering events, one backward and the other forward. ASE traveling in the backward direction will be reflected in the forward direction by DRS and experience gain due to SRS, in addition, the multiple reflections of ASE will also lower the SNR degrade NF (L. H. A. Fevrier *et al*, 2001).

Furthermore the ASE contribution, multipath interference of the signal from DRS induces limitations in the performance of the systems as for example crosstalk. DRS are proportional to the length of the fiber and the gain in the fiber, so it is particularly important in DRA (L. H. A. Fevrier *et al*, 2001).

SUL arises from the short upper-state lifetime of Raman amplification, as short as 3fs to 6fs. This virtually instantaneous gain can lead to a coupling of pump fluctuations to the signal. Usually is used backward pumping, which as the effect of introducing an effective upper-state life equal to the transit time through the fiber. For this reason in this paper we only consider backward pumping (M. M. N. Islam, 2002).

ASE is the typical noise to any optical amplifier, and is derived from the spontaneous emission of photons. At receiver, where the dominant noise component is signal-ASE, the NF can be written as (9), where G is the optical gain, h is the Planck’s constant, ω is frequency, $B_o$is the bandwidth of the optical filter, and P_{ASE} is the power of ASE and is given by (10) (H. Roger H. Stolen *et al*, 2002).

Finally, a fourth source of noise arises from the phonon-stimulated optical noise created when wavelength signals being amplified reside spectrally close to pump the wavelengths used for amplification. In other words, at room or elevated temperatures there is a population of thermally induced phonons in the glass fiber that can spontaneously experience gain from the pumps, thereby creating additional noise for signals close to the pump wavelengths. It has been shown that this effect can lead to an increase in noise figure of up to 3 dB for signals near the pump wavelength (N. P. Gavrilovic, 2001).

Note that, in (10) n_{SP} represents the inversion of population given by (11), and B_m is the bandwidth used for noise measurement, K is the Boltzmann's constant, and T is temperature in Kelvin.

$$NF=P_{ASE}/G*h*\omega*B_0 + 1/G \quad (9)$$

$$P_{ASE}=2*n_{SP}*(G-1)*h*\nu*Bm \quad (10)$$

$$n_{SP}\equiv\frac{N_2}{N_2-N_1}=\frac{1}{1-e^{((\nu s-\nu p)*\frac{h}{K*T})}} \quad (11)$$

TPS appears at room or elevated temperatures where exists a population of thermally induced phonons in the glass that can spontaneously experience gain from the pumps, thereby creating additional noise to for signals close to the pump` wavelength (O. Govind P. Agrawal, 1995).

3. Experimental work

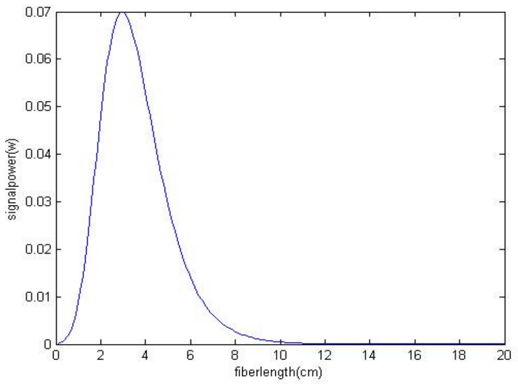
3.1 Theoretical Calculations

3.1.1 Fiber Length

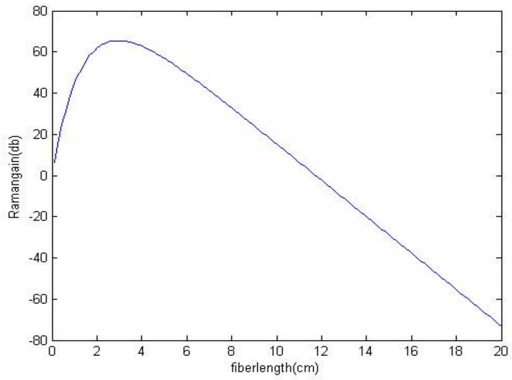
Fiber length was calculated and plotted with a signal power and Raman gain using MATLAB as shown in figure (1):

3.1.2 Threshold Power

Threshold optical power for stimulated Raman scattering in optical fiber was calculated and plotted as a function of fiber length using MATLAB as shown in figure (2):

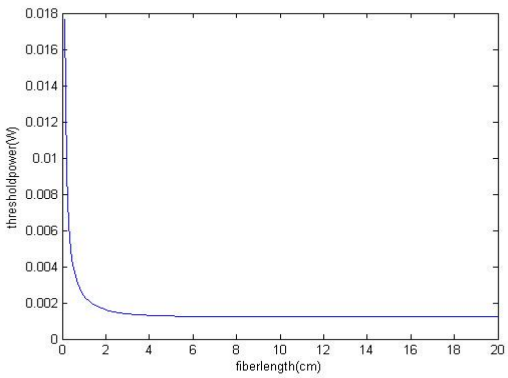


(a)

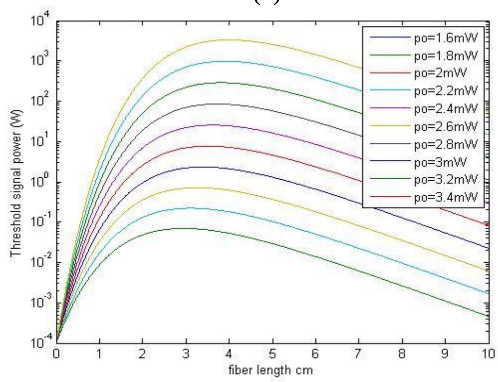


(b)

Fig.(1): (a) Signal power as a function of fiber length (b) Raman gain as a function of fiber length.



(a)



(b)

Fig.(2): (a) Threshold power as a function of fiber length (b) Threshold power as a function of fiber length with different pump powers.

3.2 Experimental setup

Figure (3) show the experimental setup of Raman fiber amplification:

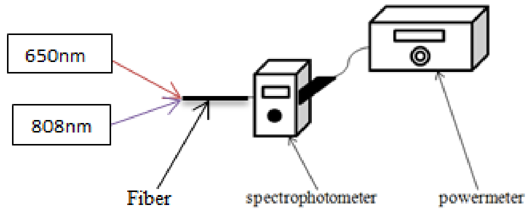
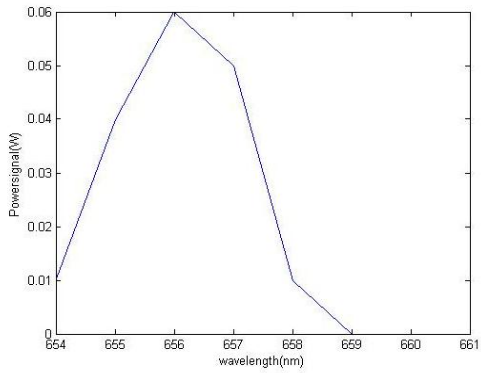


Fig.(3): Experimental setup of Raman fiber amplifier

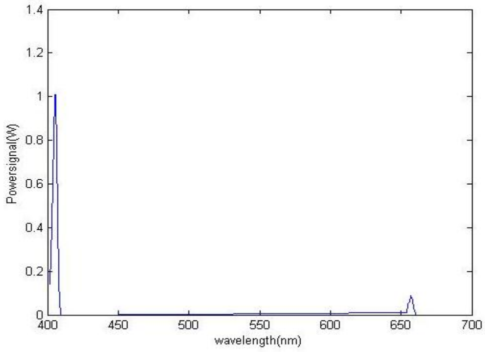
From the setup that shown in figure (3), it was shown that both pump (405nm) and signal (650nm which has high absorption by the pump wavelength) wavelengths were entered the fiber (LMA, ESM, and Hollow core fibers) with Brewster angle (8.18° and 11.25° respectively) then, the output signal was entered the spectrophotometer to vary the wavelength then the output signal power was measured for each wavelength using power meter. Then, the output signal power for the signal wavelengths 650nm was measured for each fiber using power meter in two cases:

1. When the pump wavelength OFF.
2. When the pump wavelength ON.

The curve of the output signal power as a function of wavelength was plotted using the three used fibers as shown in figures (4, 5, and 6):

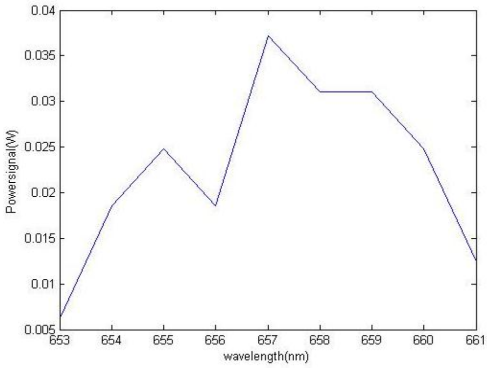


(a)

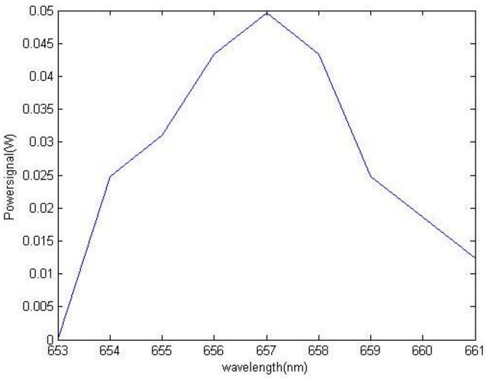


(b)

Fig.(4): Output signal power as a function of wavelength for LMA fiber at pump wavelength (a) OFF (b) ON.

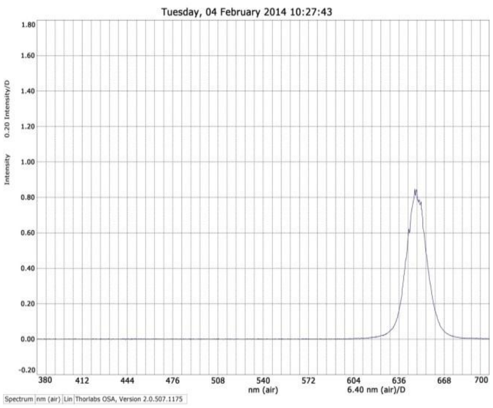


(a)

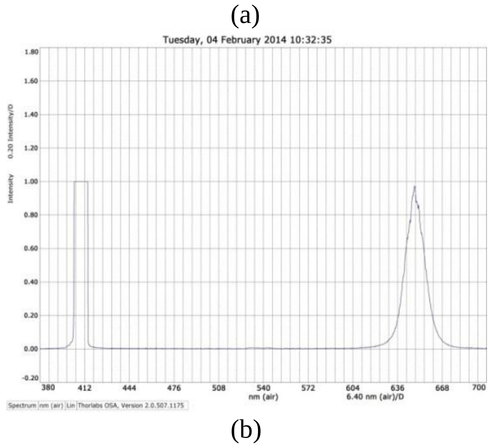


(b)

Fig.(5): Output signal power as a function of wavelength for ESM fiber at pump wavelength (a) OFF (b) ON.



(a)



(b)

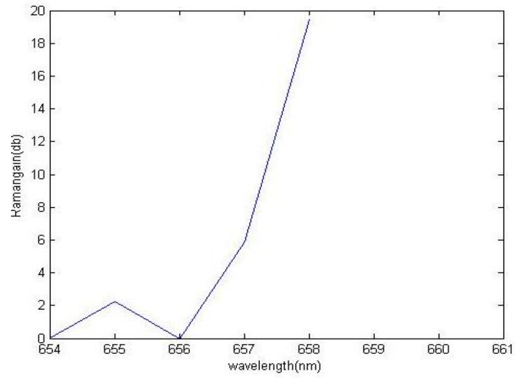
Fig.(6): Output signal power was plotted as a function of wavelength using spectrum analyzer for ESM fiber at pump wavelength (a) OFF (b) ON.

4. Results and discussion

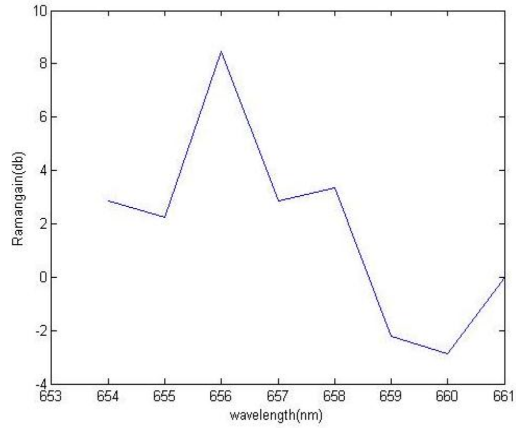
4.1 Results

4.1.1 Raman Gain

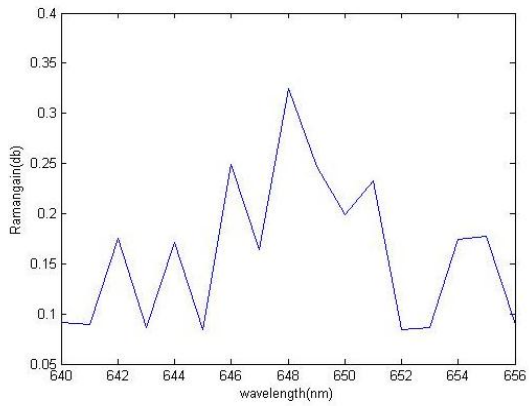
Raman gain was calculated and plotted as a function of wavelength for each fiber as shown in figure (7):



(a)



(b)

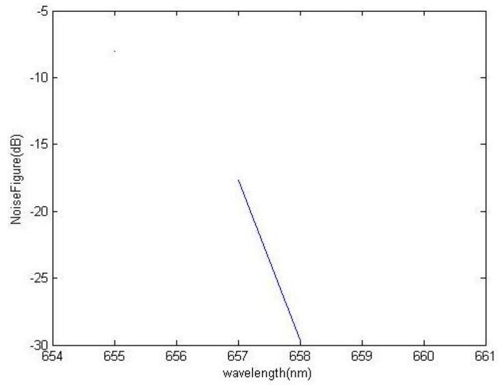


(c)

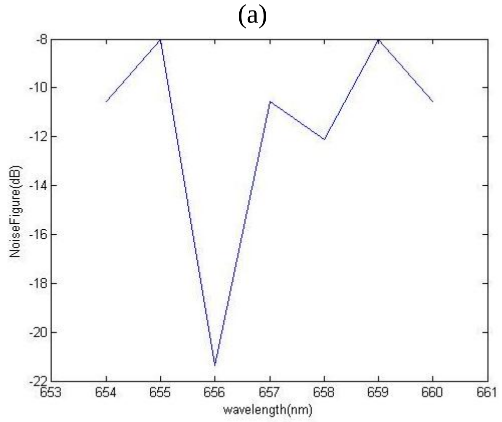
Fig.(7): Raman gain as a function of wavelength for (a) LMA (b) ESM (c) Hollow Core fibers.

4.1.2 Noise Figure

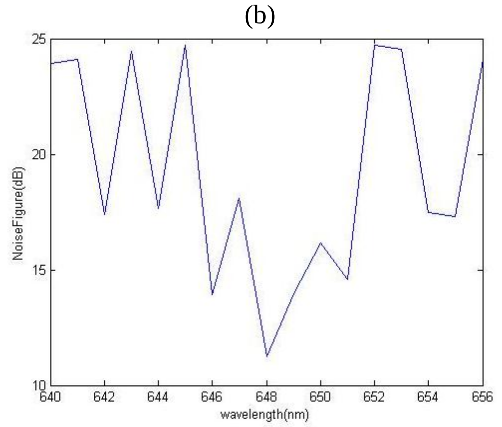
The noise figure was calculated and plotted as a function of wavelength for the three types of fiber (LMA, ESM, and Hollow Core fibers) as shown in figure (8):



(a)



(b)



(c)

Fig.(8): Noise Figure as a function of wavelength for (a) LMA (b) ESM (c) Hollow Core fibers.

4.2 Discussion

We estimated Raman gain, Raman gain coefficient, and Noise Figure for LMA, ESM and Hollow Core fibers as shown in table (1):

Table (1): Measured Raman gain and Raman gain coefficient for the three fiber types.

	LMA	ESM	Hollow Core
g_R (m.W-1)	1.354	0.737	0.197
Gain (dB)	19.46	8.473	0.325
Noise Figure (dB)	-17.71	-8.026	24.72
Wavelength of peak gain (nm)	658	656	648

Also, those three fibers were compared with EDFA, where it was shown from fig.(9) the variation of gain with fiber length for different pump powers having a constant signal input power and erbium doping density. In this figure, the gain obtained from an amplifier for eight different pump power levels were given for a 100 m long EDF when a signal input power of 100 μW was applied to the active fiber. As it was shown, the gain increases up to a certain length of fiber, and then begins to decrease after a maximum point.

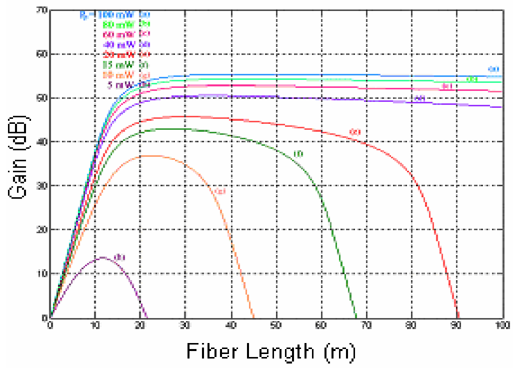


Fig.(9): The variation of gain with fiber length (P. A.Cem ÇOKRAK *et al*, 2004).

Figure (10) shows how the gain varies as a function of signal input power for different pumping powers at a constant fiber length and erbium doping density. Six different pump powers were applied to a 50 m long and the signal power was increased from –30 dBm to 10 dBm. From the figure, it was seen that EDFA gain decreases with increasing signal input power.

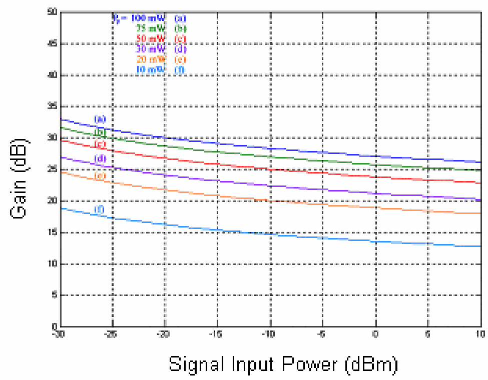


Fig.(9): The variation of gain with Signal input power (P. A.Cem ÇOKRAK *et al*, 2004).

5. Conclusion

The main conclusions drawn from this study are:
1- The fiber length was selected to be 2.5cm since this length give higher Raman gain.
2- Raman amplification was verified using the three photonic crystal fibers (LMA, ESM, and Hollow Core) that injected with olive oil.
3- It was noticed that LMA provide the highest Raman gain (19.46 dB) and lowest noise figure (-17.71 dB) among the fibers investigated, this is because LMA fiber

has the lowest losses (500 to 1700 nm) comparing with ESM and Hollow core fibers where the last one has higher losses among them.
4. it was conclude that to achieve higher gain with EDFA need 100m fiber length while with LMA fiber that used in our work the gain that was achieved about 19.46 dB with only 2.5cm fiber length.

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