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EVALUATION OF EFFECTIVE AREA OF ERBIUM DOPED FIBERS

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The effective area of an Er^{3+} doped fiber of 3% erbium concentration was studied experimentally by the transverse shift measurement method for the excitation of 980 and 1480 nm wavelengths and at the amplification range of 1520–630 nm. Based on experimental results, the fiber effective area was calculated. A comparative analysis and estimation of the results for different wavelengths of an Er^{3+} doped fiber are given.

Keywords: erbium doped optical fibers, effective area, nonlinear optical effects, WDM

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1. Introduction

The wave division multiplexing (WDM) technology makes it possible to transmit many data flows by one optical fiber. Among WDM-related amplification methods, the preference is given to the forced emission amplifiers of one class, i. e. the erbium doped optical fiber amplifiers (EDFAs). The wavelengths of optical signals amplified by C-band EDFAs are in the range from 1525 to 1565 nm. The amplifiers of the type are distinguished by a comparatively lower noise; they are little sensitive to signal polarisation, have minor connection losses, and do not introduce inter-channel distortions. The EDFA design is based on fibers with a small controlled amount of erbium (a rare earth element) added to SiO_2 in the form of Er^{3+} ion [1]. The light in the approximate range from 1530 to 1625 nm excites stimulated emission, thus achieving signal amplification, while the light of differing wavelengths passes through the amplifier invariable (Fig. 1). Almost entire inversion of Er ions could be achieved using a 980 nm excitation. Due to stimulated emission the inversion level of the exciting wavelength is usually lower if 1480 nm light is used. The quantum efficiency of the amplifier is higher at the use of 1480 nm pumping, since in this case a higher coincidence between signal and pump energies is reached [2].

An erbium doped fiber (EDF) has an interesting absorption spectrum shown in Fig. 1. There are three absorption maximums in the wavelength range used in telecommunications optical fibers. The most important for EDFAs are absorptions around 980 and 1530 nm. They are related with erbium energy levels in a silica fiber. EDFAs use the

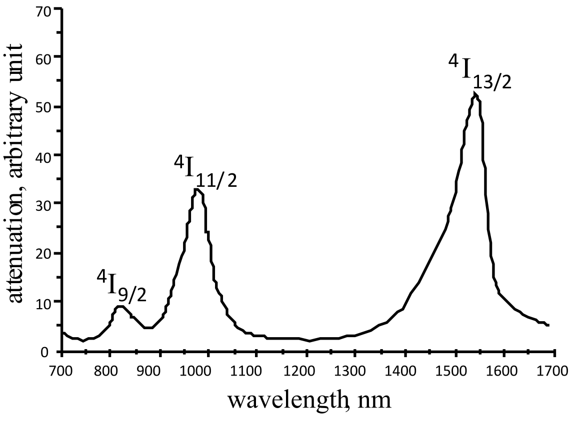

Fig. 1. Absorption spectrum of an erbium doped silica fiber [3].

energy level transition $^4I_{13/2} \rightarrow {}^4I_{15/2}$ to amplify wavelengths around 1550 nm.

The limitation of the optical field in the fiber core takes place at reaching refractivity which specifies the basic mode of field distribution. An important parameter characterising optical power and transmission is the effective area A_{eff}, which is determined by the power distribution. A standard single-mode fiber possesses a stepwise profile, and the power distribution in this case can be described by the Gaussian distribution where a greater power is obtained in the fiber centre and it is decreasing with increasing distance from it [4, 5]. The effective area value is of importance in defining the nonlinear effects in a fiber; therefore, it is useful to obtain this value for a particular optical fiber with definite optical transmission parameters [6, 7].

The aim of this research is to measure the effective area of an Er^{3+} doped fiber at different wavelength and power levels. The erbium doping level of this fiber is approximately 4%. The cladding diameter is 125 ± 1 μm, coating diameter is 245 ± 10 μm, and the cut-off wavelength is 1014 nm. The manufacturer of the fiber did not specify its effective area. Therefore, it was a challenging task to determine the optical signal intensity in this type of the fiber to continue research work for optimal EDFA parameters.

2. Experiments and results

All nonlinear effects depend on the electro-magnetic field intensity in the relevant environment. However, usually the total optical power at the fiber input and output is measured. The optical power measured at the fiber output is merely an integral from the intensity distribution over the entire area of the fiber cross-section. With this distribution being uniform, the intensity in a core with the area A_c can be calculated from the measured power P_m:

$$I = \frac{P_m}{A_c} \quad . \tag{1}$$

However, a single-mode fiber field is not distributed uniformly, besides it does not fill completely the whole fiber volume. This field is stronger along the central longitudinal axis of the fiber and decreases in the direction to the core-cladding interface, forcing into the cladding depending on the real profile of fiber refractivity. So the parameter of the effective area is introduced in order to make possible the calculations of nonlinear effects. This parameter is based on the modal field distribution and can be used in Eq. (1) instead of A_c for calculation of the optical intensity value. The effective area can be defined as

$$A_{\mathrm{eff}} = \frac{2\pi\left(\int_0^\infty |E_a(r)|^2 r\mathrm{d}r\right)^2}{\int_0^\infty |E_a(r)|^4 r\mathrm{d}r} = \frac{2\pi\left(\int_0^\infty I(r) r\mathrm{d}r\right)^2}{\int_0^\infty I^2(r) r\mathrm{d}r}, \tag{2}$$

where $E_a(r)$ is the amplitude, and $I(r)$ is the intensity of the near-field of the fundamental mode at a distance of radius r from the central longitudinal axis of the fiber [3].

There are several methods how to measure the optical fiber effective area: near- and far-field optical radiation scanning as well as close distance imaging using CCD cameras. In this investigation, the effective area was determined through the transversal shift measurements, i. e. a far-field distribution measurement method. This method is based on a two fiber end transversal shift using a micro-positioner to perform the key operations: positioning of the optical fiber and shifting it in the direction perpendicular to its longitudinal axis. It is a simple but sufficiently accurate measurement method for the evaluation of A_{eff}. We have used this technique previously to determine the optical fiber effective area, and calculations showed that uncertainty of results is in the range of 5% [8]. The main cause of measurement errors are the power metre and micro-positioner precision. Due to the need for specific equipment we did not have the opportunity to perform the same measurements using a different measurement technique.

The transition of optical power from the source fiber's central mode to the same mode of the receiving fiber can be described by the integral relationship over the area:

$$C(u) = \iint_S E_a(|r|) E_a(|r-u|) \mathrm{d}r, \tag{3}$$

where $u = |u|$ is the shift from the fiber's central axis. The integrals are taken over the entire area (S) where both fiber modes are overlapping. Integral (3) can be written in polar coordinates, which gives:

$$C(u)=\int_0^{2\pi}\int_0^{\infty} E_a(r)E_a(r')r\,\mathrm{d}r\,\mathrm{d}\theta=\left[E_a(r)*E_a(r)\right]_{r=u},\quad(4)$$

where $r'^2= u^2+r^2-2ru\cos(\varphi)$ and * sign denotes a two-dimensional convolution. The Hänkel transformation convolution is described by the expression

$$H\{C(u)\}=H\{E_a(r)*E_a(r)\}=F^2(p),\quad(5)$$

where $F^2(p)$ is the far-field power distribution in the fiber. Using equations (3) and (4) the power $C^2(u)$ transferred from one fiber to the other can be obtained for the central mode of the near-field power distribution by calculating it through the far-field power distribution. Further effective area can be obtained using the near-field power distribution.

In the measurements it is necessary that fiber ends are fully identical, since they should be placed precisely opposite to each other. The placement of the fibers on parallel planes was done by fixing them by fasteners arranged in parallel, each fiber being fixed by its opposite parallel fastener. One of the fasteners is immovable, securing the fiber with an optical radiation source at its second end. The second (receiving) fiber is placed on a movable platform, whose position can be varied by three stepping motors. Therefore, the receiving fiber could be centred against the source fiber thus achieving the maximum power of the transmitted optical signal. Actually, the connection of two ends of a fiber being formed, by varying the position of one of the fibers we could receive the maximum transmitted power. As a result of measurements, the far-field power distribution in fiber cross-section was obtained. Then it was necessary to derive from this distribution the near-field power distribution and, finally, to calculate the value of the effective area of the fiber. In the measurement set-up (Fig. 2) there are also tunable laser sources in the range of 1520–1630 nm and 1465–1575 nm and a 980 nm laser diode. Lasers provide optical radiation with the optical signal power up to +13 dBm (20 mW). For optical power measurement at the output of the created optical connection the power and wavelength metre is used.

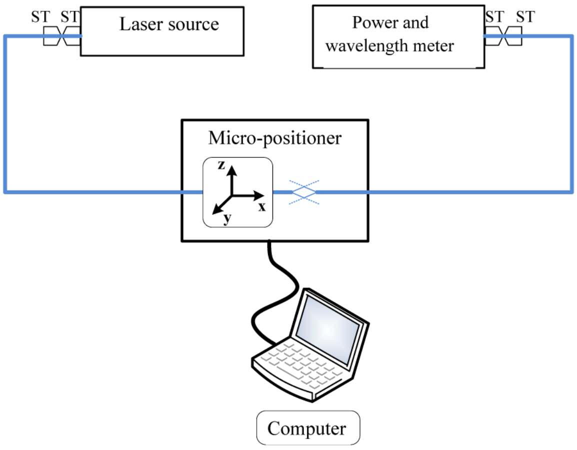

Fig. 2. The block diagram of the measurement breadboard.

In our experiment the measurements were taken at various parameters of the source's optical signal, with the power and wavelength of the optically issued signal varied. The purpose of such variations was to study the dependence of the effective area of an Er doped fibre on the two mentioned parameters. The results of measurements for one of wavelengths are shown in Fig. 3.

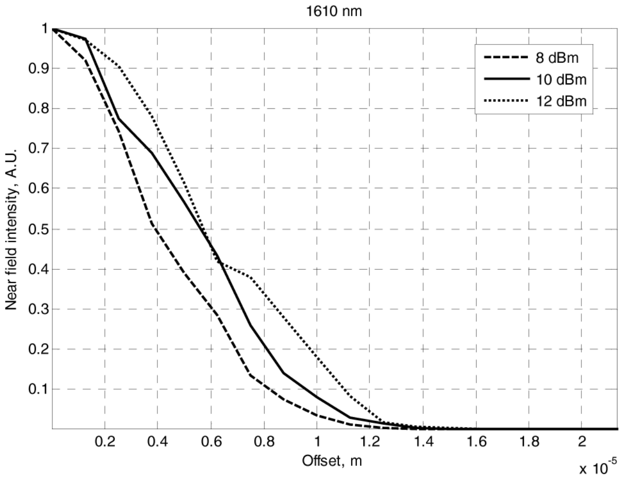

Fig. 3. The measured power distribution vs. fiber transverse shifting at 1610 nm and three input optical radiation power levels (8, 10 and 12 dBm).

3. Discussion

Based on the measured power distribution results and the model for their processing described above the fiber effective area values are calculated. In total, 21 different effective area values are calculated for seven different optical wavelength and three different input optical power levels. Table 1 presents the EDF effective area results calculated using our written script in MatLab software.

Table 1. The measured Er^{3+} doped fiber effective area for different wavelength and power values of the optical signal.

	A_{eff}, μm^2		
λ, nm	P_{in} = 8 dBm	P_{in} = 10 dBm	P_{in} = 12 dBm
980	49.50	50.46	51.42
1480	61.91	65.21	68.51
1520	64.33	70.34	72.07
1550	67.03	68.28	70.72
1580	67.16	68.95	72.00
1610	67.48	69.48	73.21
1630	68.32	70.77	76.34

The values of the fiber effective area are in the range from 49.50 μm^2 at λ = 980 nm and P_{in} = 8 dBm to 76.34 μm^2 at λ = 1630 nm and P_{in} = 12 dBm. It is clearly seen that for 980 nm the measured effective area is considerably smaller than for other wavelengths. The explanation for this is that one of absorption maximums is at λ = 980 nm. This wavelength is widely used as a pump in EDFAs because of erbium ion effective excitation to $^4I_{11/2}$ level (Fig. 1).

The results of the effective area for other wavelengths show closer dispersion so they were plotted in one graph (Fig. 4) for better understanding.

The standard ITU-T G.652 single mode fiber effective area is evenly increasing at a larger wavelength. For EDF, results are similar as we can see from Fig. 4. It shows the dependence of the measured effective area on the optical signal wavelength at three different power levels, 8, 10, and 12 dBm. This dependence, in contradistinction to the standard single mode fiber, is not even. We can see the local maximum around 1520 nm wavelength. To explain this we should look at the EDF absorption spectrum around 1420–1620 nm wavelength.

There is a marked absorption maximum around λ = 1530 nm. But at the same time this wavelength overlaps with the EDF gain maximum when optically pumped at a definite wavelength (980 or 1480 nm). So we can conclude that effective area measurements interpret EDF characteristics as well as absorption spectral measurements due to similar wavelength dependence. To understand better, A_{eff} change measurements should be performed with a smaller wavelength step to achieve more detailed information.

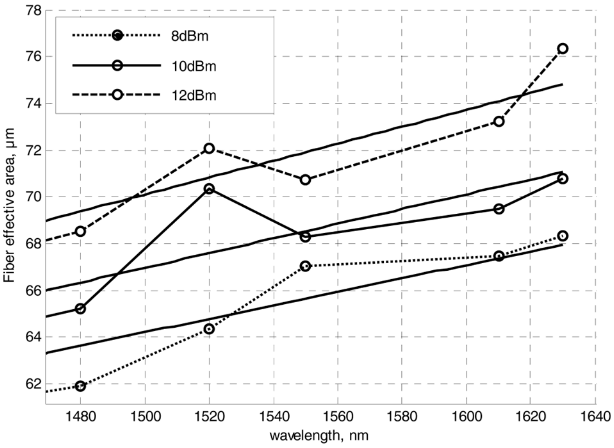

Fig. 4. Er doped fiber effective area vs. wavelength (nm) at three different optical power levels.

A_{eff} measurements can give useful data about the fiber and optical signal propagation characteristics in it. These data would be useful for further improvement of EDFA amplification characteristics, for example a more even gain at the whole spectral range of amplification. EDF with more complicated profiles could be used to achieve necessary optical signal intensity at a different wavelength.

4. Conclusions

Although the EDFA amplification depends on the length of a doped fiber, it can be seen that its effective area changes determine the nonlinear optical effects generation, since at the input a large optical power is concentrated. The input power of the optical signal to be amplified plays a very important role in long communication lines where a great number of EDFAs are applied. The EDFA amplification changes depend on the signal wavelength. The changes originate from the erbium emission and absorption profiles (Fig. 5). There are C-band, L-band, and wide-band EDF amplifiers. The EDFA amplification is maximal at 1530 nm, nonlinearly

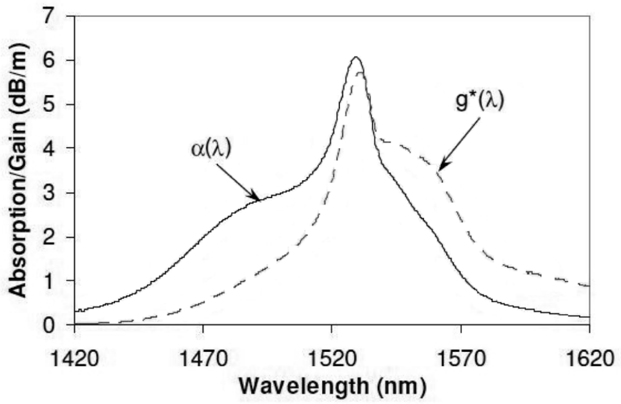

Fig. 5. Absorption (α) and gain (g^*) parameters for an Er doped fiber [9]

decreasing from this wavelength. Due to nonlinear changes in the amplification coefficient, nonuniform amplification in the WDM system channels occurs. The difference in the channel levels can reach 2 dB if these channels are in the proximity of 1555 nm zone, and 10 dB if these channels are in the entire 1530–1565 nm C-band in the case of one amplifier. This research gives us a good EDF A_{eff} evaluation. It is clear that EDF absorption and amplification characteristics affect fiber effective area which is actually the cause of these effects due to the optical signal intensity change. Our further research includes EDF A_{eff} measurements around $\lambda = 1530$ nm and EDF nonlinear coefficient determination using picosecond optical pulses.

Acknowledgments

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ŠVIESOLAIDŽIŲ SU ERBIO PRIEMAIŠOMIS EFEKTYVIOJO PLOTO ĮVERTINIMAS

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Santrauka

Eksperimentiškai tirtas optinių šviesolaidžių su erbio priemaišomis efektyvusis plotas naudojant skersinio poslinkio matavimo metodą 980 ir 1480 nm bangos ilgių sužadinimui ir esant stiprinimo ruožui nuo 1520 iki 1630 nm. Remiantis eksperimentų rezultatais, suskaičiuotas šviesolaidžio efektyvusis plotas. Straipsnyje pateikta rezultatų lyginamoji analizė ir įverčiai skirtingiems bangų ilgiams šviesolaidyje su Er^{3+} priemaišomis.