# Er-doped concentric-cores optical fiber for simultaneous amplification and compensation of positive dispersion

**Pramod R. Watekar**[1], **M. L. N. Goswami**[1], **H. N. Acharya**[1], **J. C. Biswas**[2], and **B. P. Pal**[3]

[1] *Optical Fiber Unit, CRF and Department of Physics and Meteorology;*
[2] *Department of Electronics and Electrical Communication Engineering,*
*Indian Institute of Technology, Kharagpur-721302 India*
[3] *Department of Physics, Indian Institute of Technology, New Delhi-110016 India*

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The Er-doped concentric-cores dispersion compensating fiber (EDDCF) has been demonstrated. The rare earth has been doped as a ring around the inner core. We have obtained 14-dB gain at 1550 nm (using 100-mW pump power and 980-nm wavelength) with dispersion of about −165 ps/(km·nm). It is useful for the optical fiber network where amplification as well as negative dispersion are necessary.

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To avoid the dispersion related bit rate penalty in the optical fiber long haul networks, the dispersion-shifted fibers (DSFs) that offer zero dispersion at 1550 nm are employed. However, some positive dispersion is deliberately kept in the multi channel high-speed long haul networks to avoid nonlinear effects and hence, non-zero dispersion fibers are used in such networks[1]. The positive dispersion in the network starts affecting the bit rate once the cumulative dispersion in the fiber becomes higher because of longer lengths. The dispersion compensating fiber (DCF) that has negative dispersion is used in the above network so that the total dispersion in the link is cancelled. The optical amplifiers are also employed along with the DCF to overcome the losses in the link. Earlier, design[2,3] and realization of the DCF with dispersions of (i) around −1800 ps/(km·nm) at 1550 nm[4] and (ii) around −1750 and −800 ps/(km·nm) at wavelengths of 1470 and 1550 nm respectively[5] have been reported.

In this paper we are presenting the results of realization of the concentric cores fiber with $Er^{3+}$-doped as the ring around the inner core for simultaneous amplification and negative dispersion at 1550 nm.

The preform with two concentric cores has been fabricated using the modified chemical vapor deposition (MCVD) process and the layering is shown in Fig. 1.

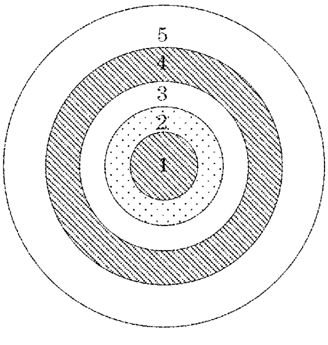

Fig. 1. Profile of the fiber fabricated using MCVD. Layer 1: inner core; layer 2: Er-doping; layers 2 and 3: inner cladding; layer 4: outer core; layer 5: outer cladding.

Initially a few buffer layers of $SiO_2$ are deposited into the quartz tube to prevent the diffusion of hydroxyl ions into the core from the quartz tube. A care has been taken to sinter each layer before deposition of the next layer. This is necessary to avoid the bubble formation. The outer core has been deposited using $SiO_2$-$GeO_2$ layers and depositing required layers of $SiO_2$ forms the inner cladding between the two cores.

The diameter of the inner-core of the Er-doped concentric-cores dispersion compensating fiber (EDDCF) is much less as compared to the core of ordinary CSF and the pre-deposition technique is utilized to deposit the core where the dopants for core i.e. $GeO_2/SiO_2$ are deposited at the very last pass before the collapse. Hence, it has been impractical in our case to deposit the Er-ions into the core and we have chosen the inner cladding layers that are adjacent to the core for depositing the Er-ions. Thus, it forms the ring around the inner core. A few layers of $SiO_2$ in the inner cladding, adjacent to the inner core are left unsintered and thus, forming the soot. For depositing the Er-ions into the preform, we have used solution-doping technique[6]. The solution of $ErCl_3$ and $Al_2O_3$ into the distilled water has been inserted into the tube with soot and is kept soaking for an hour. The tube is then dried using optical lathe and collapse is started at about 2050 °C. The inner core is deposited at the pre-collapse stage using suitable ratio of dopants $GeO_2$ and $SiO_2$. This ensures a very narrow core and it also decreases the axial index dip in the core of optical fiber. Finally the tube is collapsed at 2050 °C to give a preform.

The fiber with total diameter including cladding is drawn at 125 $\mu$m using Heathway six-meter high fiber draw-tower and the diameter has been maintained within ±1 $\mu$m. A few hundred meters of the fiber has been drawn to carry out the characterization. The refractive index (RI) profile of the fiber scaled from the RI profile measured with preform using P104 is shown in Fig. 2. The Er-ring is not seen in the RI profile of Fig. 2, indicating that the Er-doping has not caused any significant refractive index change.

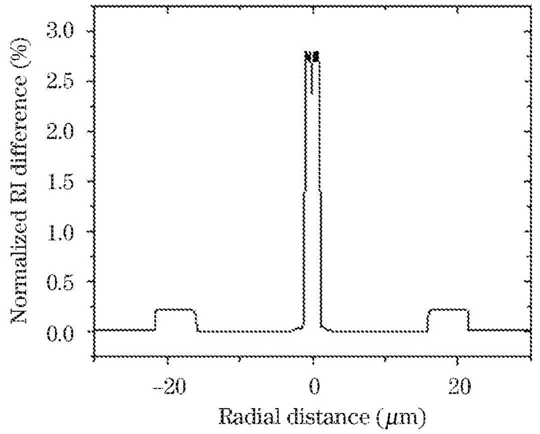

Fig. 2. RI-profile of the fabricated optical fiber using MCVD.

**Table 1. Measured Characterizing Parameters of the EDDCF**

| Measured Parameters | Value |
|---|---|
| Er-Ion Concentration | 21 × $10^{24}$ ions/$m^3$ |
| Experimental Cutoff Wavelength | 970 nm |
| Fluorescence Lifetime at 980-nm Pump | 10 ms |
| Attenuation at 1.55 μm | 0.24 dB/m |
| Attenuation at 980 nm | 0.41 dB/m |
| Dispersion at 1550 nm | −165 ps/(km·nm) |

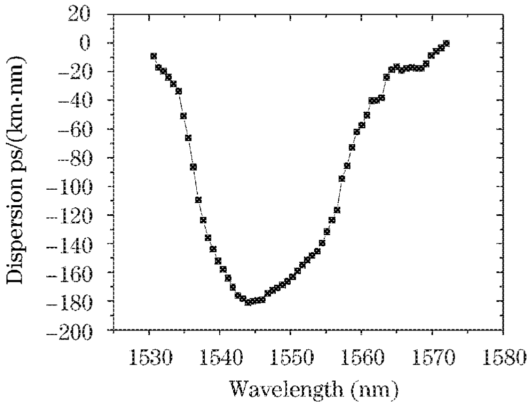

Fig. 3. Spectral variation of the chromatic dispersion.

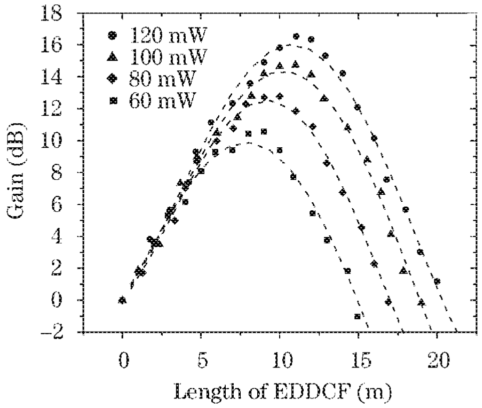

Fig. 4. Amplification characteristics of the EDDCF at 1550-nm signal wavelength using different pump powers (980-nm wavelength).

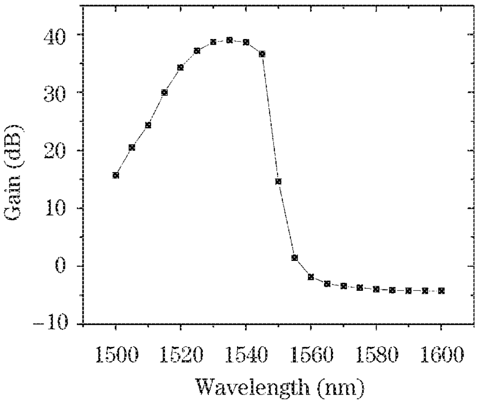

Fig. 5. Spectral variation of the gain at 10-m EDDCF and the pump power used is 100 mW (980-nm wavelength).

Attenuation of the EDDCF is determined using a cutback method (using a Bentham optical characterization instrument) and the attenuation at 1.55 μm is 0.24 dB/m and at 980 nm it is 0.41 dB/m. The higher concentration of dopants and narrow single core has contributed in the increased loss at 1550 nm. The dopant concentration and radial depth of dopants in the cladding have been determined using scanning electron microscopy and energy dispersion analysis using X-ray system (Model: JEOL-JSM 5800). The fluorescence-lifetime of the excited Er-ions is determined from the decay characteristics of the emission and by finding the 1/e decay time constant. All the measurements are repeated for several times. The obtained results are listed in Table 1.

The chromatic dispersion of the fiber is measured using a York Technology chromatic dispersion-measuring instrument (Model: CD S18), which employs phase shift method. The measured dispersion is around −165 ps/(km·nm) at 1550 nm and the full-width-half-maximum (FWHM) band is measured to be 20 nm around 1545 nm. The spectral variation of dispersion is shown in Fig. 3.

The amplification supported by the optical fiber is measured by applying input signal (1550 nm) coupled with pump signal (980 nm) in co-direction pumping scheme using WDM coupler and is fed into the EDDCF. The output spectrum has been obtained using spectrum analyzer (Model: HP-70004A). Variation of measured gain with respect to EDDCF length at different pump powers and at 1550-nm signal wavelength is shown in Fig. 4. It can be noted that the gain at 100-mW pump power and 10-meters length is around 14 dB. The spectral variation of the gain is also measured at 10-meter EDDCF and is shown in Fig. 5. Noise figure (NF) of the EDDCF at 980-nm pumping is determined at 1-nm wavelength bandwidth around the signal wavelength. NF at 10-m with pump power of 100 mW is found to be 4.8 dB at 1550 nm.

As a conclusion, we have fabricated and characterized the Er-doped double-core dispersion compensated fiber. The dispersion at 1550 nm is about −165 ps/(km·nm) and gain is 14 dB at 10-m length when pump wavelength of 980 nm (100-mW power) is utilized. The bandwidth of simultaneous amplification and dispersion is around 20 nm and it is suitable for the C-band communications. The NF measured at 1550 nm is 4.8 dB. Though the realization presented in the current work is for a small negative dispersion because of smaller distance of amplification, just reduction in the erbium-ion concentration will result in increased length to attain the required gain and thereby increasing the negative dispersion.

H. N. Acharya is the author to whom the correspondence should be addressed, his e-mail address is fiber@phy.iitkgp.ernet.in.

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