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Fabrication of a new kind of single mode large-mode-area erbium-doped fiber and its applications

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Step-index (SI) fiber designs are commonly used in achieving large mode area (LMA) and single mode operation in fiber lasers. A new kind of fabrication method of single mode LMA EDF is reported in this paper, the key process is deposition of multi-layer-core structure by using modified MCVD. Further more, the key optical and geometric specifications of the fiber are measured: the absorption peak is 7.4 dB/m @ 980 and 19 dB/m @ 1530 nm; the cutoff wavelength is about 1176 nm; the mode field diameter (MFD) is 12.4 μm and 12.6 μm at 1550 nm according to Petermann-2 and Gaussian definitions, respectively; the core and cladding diameter is about 12 μm and 124 μm, respectively. The MFD of conventional standard EDFs is in a limited range ~5-8 μm, thus the experimental result has made a big progress for MFD. Then the homemade LMA EDF is used to make a linear-cavity EDF laser (EDFL) based on TFBG and OC. A stable lasing output with a 3-dB bandwidth of less than 0.03 nm, a power perturbation of less than 0.22dB and a wavelength shifts of less than 0.012 nm over 2h are achieved at room temperature.

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1. Introduction

The area of EDF lasers has undergone rapid developments in recent years. Gone are the days when fiber lasers were seen as something of an irrelevant curiosity, offering interesting performance features, but always with power levels or other performance limitations, that made them unsuitable for all but a few applications. Improvements in the area of high-power, high-brightness semiconductor pump lasers, and the development of techniques, such as cladding-pumping, have changed this viewpoint markedly. Moreover, major advances in fiber Bragg grating fabrication and more sophisticated fiber designs and pump coupling techniques, have at the same time improved device performance and increased the versatility, functionality and practicality of the technology; allowing the development of a broad range of robust, practical optical sources [1-5].

The key to achieving increased pulse energies and peak powers has been to increase the MFD within the fiber. From an energy applications perspective this enables more energy to be stored within the structure before ASE, or lasing due to the ultimately unavoidable back reflections, limits the storage capacity. The energy stored scales more or less in proportion to the mode area. A large MFD is good from a pulse peak power viewpoint since it reduces the optical intensity within the core and reduces the impact of optical nonlinearities. As an illustration of the limits of conventional fibers a standard erbium doped fiber operating at 1550 nm has an MFD in the range ~5-8 μm and allows energy storage of ~10-20 μJ. Tolerable power levels within such a fiber might be in the range 100 W-1 kW, depending on the device length and the particular application in mind. Note that large core fibers are not just useful for pulsed lasers. As continuous-wave laser powers continue to in-crease nonlinearity and power handling will also become a major issue, pointing to the need for fiber with large mode sizes. Moreover, in cladding-pump schemes, the pump absorption length scales with the relative ratio of core and cladding area. Larger core sizes thus mean shorter device lengths- a desirable feature in almost all instances. The need for large core fibers is thus self evident, however the core size of a fiber cannot be arbitrarily increased without penalty. Single mode operation, a fundamental requirement for many applications, can only be maintained for a restricted range of core diameters. As the core diameter is further increased a fiber becomes multimode and therefore less useful from an applications perspective. In order to maintain the fiber is single mode, the low numerical aperture (NA) is required. This paper discusses a kind of fabrication method of LMA EDF.

2. Theoretical analysis

Single-mode behavior can be considered in terms of the fiber's V parameter (dimensionless frequency), and V is defined with following formula

$$V = (2\pi\lambda)\cdot a \cdot NA \quad (1)$$

where λ is the wavelength of light, *a* is the core radius, and NA is the numerical aperture. For single-mode operation one requires V<2.405. In principle, a lower cutoff wavelength could be achieved by either reducing the NA at fixed core dimension. And the MFD is defined by Petermann-2 and Gaussian approximation as following expressions (0<V<2.405) [6]

$$MFD_P = 2w_P = 2\left[\frac{2\int_0^\infty \psi^2(r)rdr}{\int_0^\infty \left(\frac{d\psi}{dr}\right)^2 rdr}\right]^{1/2} \quad (2)$$

$$MFD_g = 2w_g \cong 2a\left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.870}{V^6}\right) \quad (3)$$

where w_P and w_g is the mode field radius according to Petermann-2 definition and Gaussian approximation, respectively. $\psi(r)$ represents the transverse field pattern of the fiber. a is the radius of fiber.

We consider one kind of multi-layer-core structure discretionarily. The refractive index profile is shown in Fig. 1. In order to know this kind of fiber, the MFD of this fiber can be simulated by Matlab simulation. And the simulation results are plotted in Fig. 2.

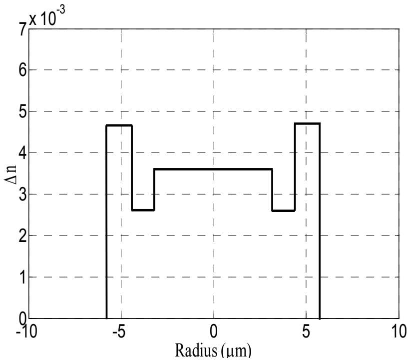

Fig. 1. Schematic diagram of refractive index profile of one kind of LMA EDF.

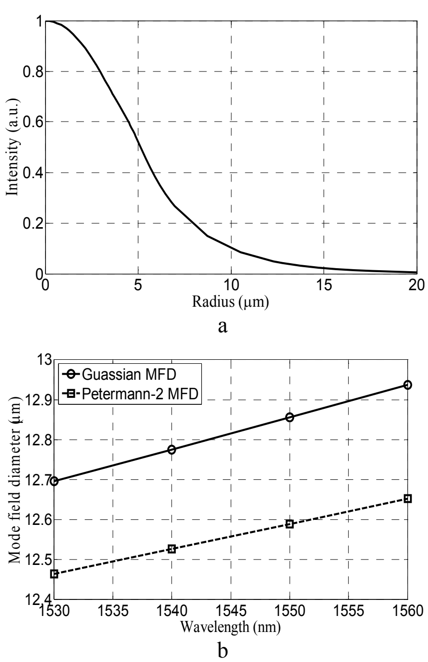

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Fig. 2. The MFD specifications of the fiber. (a) The distribution of the MFD. (b) The MFD vs. wavelength.

Obviously, the EDF with this structure has a larger MFD in contrast with classical EDF. That is to say if the core layer is changed by manufacture process, especially by realizing multi-layer in the core area, the NA of the EDF will have a great potential to be decreased and the MFD will become much larger.

3. Experiments

3.1. Fabrication of LMA EDF

First, the erbium-doped perform should be fabricated. Here, the MCVD lathe used in our experiments is shown in Fig. 3, which is designed in our laboratory. It is different with traditional MCVD lathe, which used the carbon furnace instead of oxyhydrogen torch. The biggest advantage of this carbon furnace is that it can increase the longitudinal uniformity of the manufactured perform. The refractive index profile of the fiber we want get is like Fig. 1.

Fig. 3. The modified MCVD lathe with a carbon furnace in our laboratory.

Perform is fabricated from substrate tubes (Heraeus QUARZGLAS) of approximate dimensions 18mm (outer diameter) and 15 mm (inner diameter) with 40cm length. The selected tube is first immersed in Hydrofluoric Acid (HF) for 15 min at room temperature, and then is washed clearly by deionized water (resistivity >15MΩ•cm). At last, the tube is blown dry with high purity nitrogen. Finally, through typical RE doped MCVD process, the perform has been obtained. The most important process of fabricating LMA EDF is to get the multi-layer-core structural fiber. In fact, the multi-layer structure is caused by the different refractive index between the adjacent layers. To realize multi-layer-core structural fiber, germanium and fluorine is doped during the deposition process, and the quantity of them should be controlled accurately. The most important and difficult step during the manufacturing process of perform is deposition of porous layer. If the depositing temperature is suitable, the SiO_2 particles size which deposited on the porous layer is rather small. Then they form loose spacing, so the porous layer could absorb more doping solution, it is beneficial to the high concentration erbium doping in silica-based fiber. In addition, the perform formed by the porous core layer fabricated at suitable temperature could make the doping distribution more uniform, and there are less burrs on the core-cladding boundary; If the porous layer depositing temperature is too high, the SiO_2 particles size which deposited on the porous layer was rather big, that would make a part of the porous layer vitrified. Although it was beneficial to the immersion and absorption of solution, erbium doping in core area of perform will be nonuniform, even crystallized; if the porous layer depositing temperature is too low, firstly, the SiO_2 particles size which deposited on the porous layer is extraordinary small. Secondly, the reaction rates of SiCl4 and GeCl4 are not high enough, so the deposited porous layer might be too thin, especially, the adhesion between porous layer and barrier layer will become bad. This will not only be against the solution immersion, but also cause the porous layer drop off the inner surface of barrier layer during dehydration or vitrification process. So it is very important to select an optimal depositing temperature of porous core layer. Choosing an optimal temperature can not only control the density of the porous core layer, but also maintain the uniformity of solution doping and avoid crystallization [7-10].

Fig. 4 shows the main different states of the fabrication process of perform.

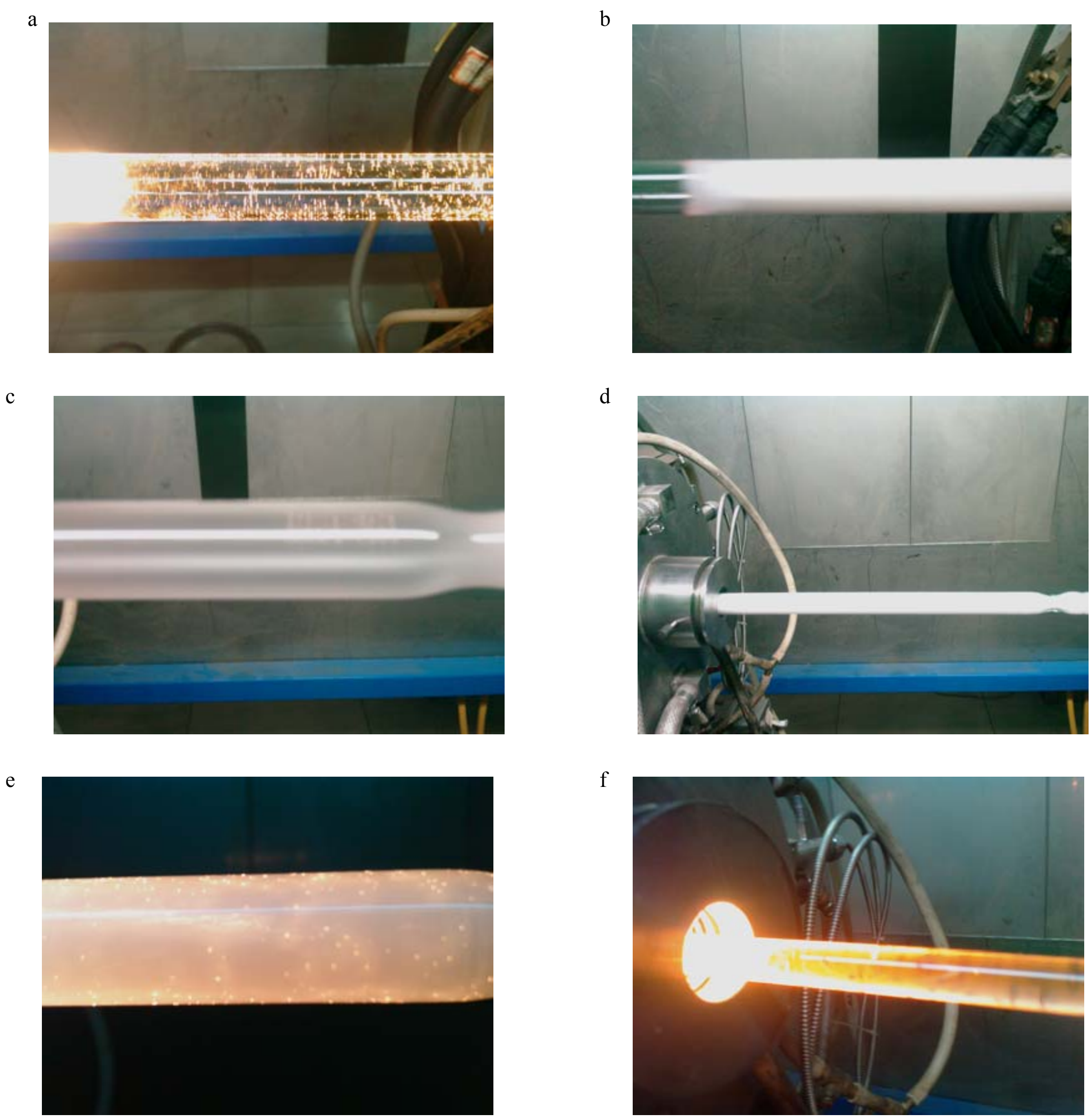


Fig. 4. Six main states of the fabrication process of perform. (a) Polishing and deposition of barrier layers. (b) Deposition of porous layer. (c) The thin film status after solution-doped. (d) Dehydration. (e) Vitrification. (c) Tube collapse.

Before drawing the fiber, the perform is tested by using P104 (YORK, UK) perform analyzer to measure optical and geometrical characteristics. That is to prepare for next steps: sleeving and drawing. The purpose of sleeving is to make sure its cutoff wavelength is out of the band we used. Fig. 5 shows the refractive index profile of the self-made EDF. Finally, the self-made perform is pulled to the fiber by using drawing tower in our laboratory.

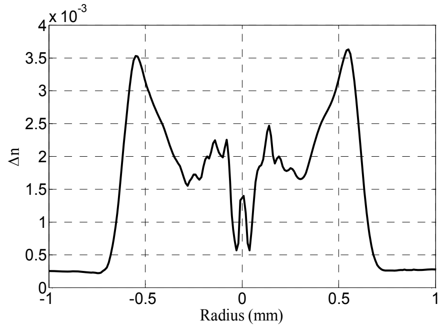
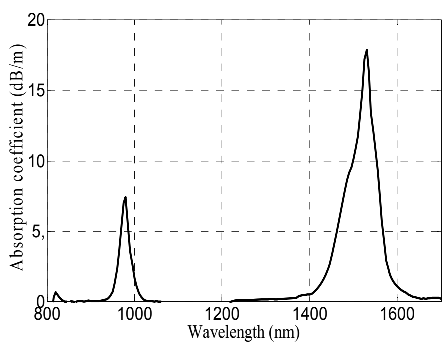


Fig. 5. The refractive index profile of the self-made perform.

3.2. Measurements and results

After above process, the EDF was obtained. In order to find if the self-made EDF is a kind of LMA EDF, we tested main characteristics of the EDF by using professional optical measuring instruments in our laboratory. The absorption spectrum, cutoff wavelength and MFD of the fiber were tested with PK2200 (Photon Kinetics, USA) series optical fiber analysis systems, the tested results were shown in Fig. 6; the refractive index profile, geometrical parameters (core and cladding size) and MFD distribution of the core were tested with NR9200 (EXFO, USA) optical fiber analyzer, the tested results were shown in Fig. 7.



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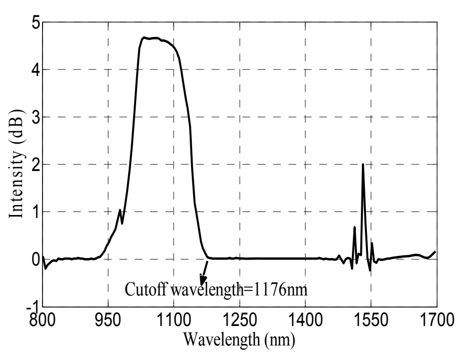

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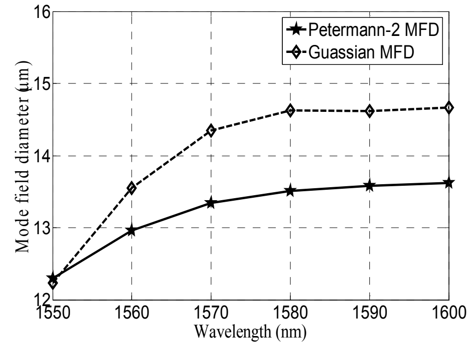

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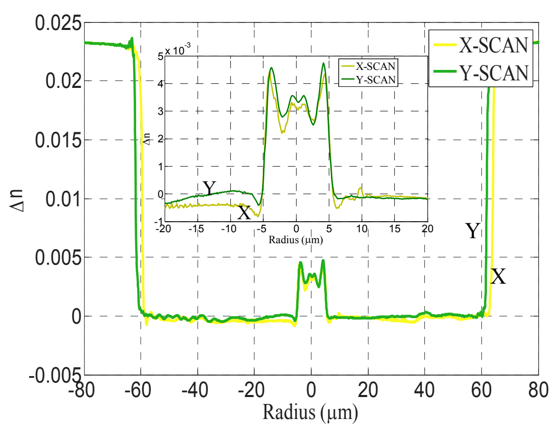
Fig. 6. The results were tested by PK2200. (a) This is the absorption spectra of the EDF, and the absorption peak is 19dB/m @ 1530nm. (b) The cutoff wavelength is 1176nm. (c) The relationship between MDF and wavelength. Actually, there are two curves, because the instrument produces the MFD according to Petermann-2 and Gaussian definitions.



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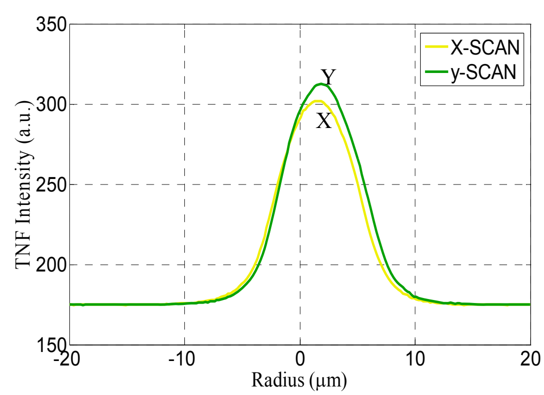

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Fig. 7. The results were tested by NR9200. (a) The refractive index profile of the EDF, and the core and cladding size is clear. (b) The MFD distribution (Petermann-2 definition).

From above figures, the most important and interesting parameters are solved. The cutoff wavelength is about 1176 nm, so when fiber works at C-band it is a single mode fiber. The absorption peak is 19 dB/m at 1530 nm, which is rather high and better than some commercial EDFs, e.g. Er 1550C and Er 1550C3 of Corning incoperated. The MDF is about 12.4 µm at 1550 nm by using PK2200 according to Petermann-2 definition, which fits the simulation value 12.6 µm well in Fig. 1. The Gaussian MFD is just a reference value, because the fundamental mode field can't be always approximated well by a Gaussian function. The error between measured value and simulation results of MFD is caused by several reasons; the biggest of all is that it is difficult to control the refractive index of every layer, which is a technological problem. The core diameter is about 12 µm, and the cladding outside diameter is about 125 µm, which accord with the size of standard single mode fiber (SMF) very well. When this kind EDF is spliced with standard SMF, the insertion loss can be controlled within 0.1dB. According to these advantages, the EDF which was fabricated with deposition of multi-layer-core method has a great potential in practical applications.

3.3. Fiber laser based on LMA EDF

The configuration of the proposed fiber laser is shown in Fig. 8. The linear-cavity consists of a WDM coupler (980/1550 nm), a three-port optical circulator (OC), one tunable fiber Bragg grating (TFBG), an isolator and a 0.5 m long homemade LMA EDF which is discussed above. By directly fusing the port 3 to port 1, a full reflective mirror is made. The insertion loss form port 1 to port 2 and from port 2 to port 3 is 1dB and 1.1dB, respectively. The TFBG has two functions in this configuration. Firstly, it works as a particially-reflecting-mirror, by which a complete laser resonant cavity is then constructed by TFBG and OC. Secondly, the TFBG acts as a lasing wavelength selector. The uniform FBG used in TFBG is made in Hydrogen loaded G652 Fiber based on a phase-mask technology, whose original transmission spectrum is shown in Fig. 9 with central wavelength at 1543.6231 nm. The FBG has such a narrow 3 dB bandwidth of 0.03 nm that it can serve as not only a particially-reflecting-mirror but also as a narrow-band filter. For this advantage, it can reduce mode competition and enhance wavelength stabilization. The spectral characteristics of the lasing lines are observed in an optical spectrum analyzer (Ando Corporation, model AQ6317C with a resolution of 0.01 nm).

By increasing the pump power, a stable output is obtained, which is shown in Fig. 10. The 16-time repeated scan of lasing spectra over 15 min is shown in Fig. 11. Obviously, the output power fluctuations and the wavelength shifts are controlled within a limited range, which are measured to be less than 0.22dB and 0.012 nm over 2h.

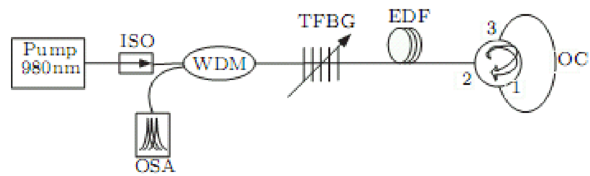

Fig. 8. Configuration of the linear-cavity EDFL based on TFBG and OC.

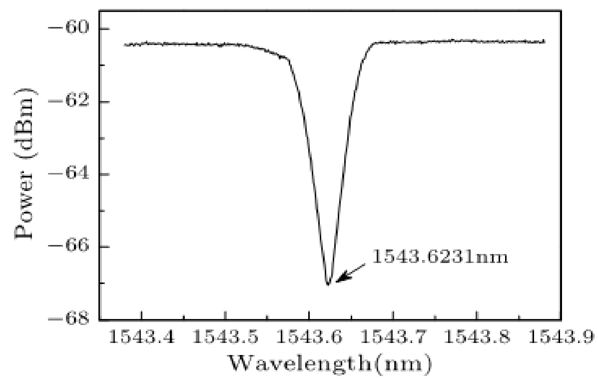

Fig. 9. Original transmission spectrum of TFBG.

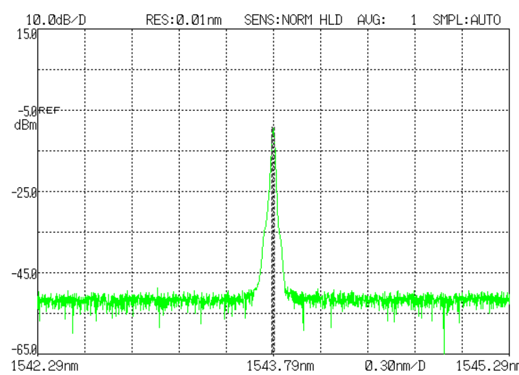

Fig. 10. Output spectrum of the EDFL, a stable and narrow-band peak is observed.

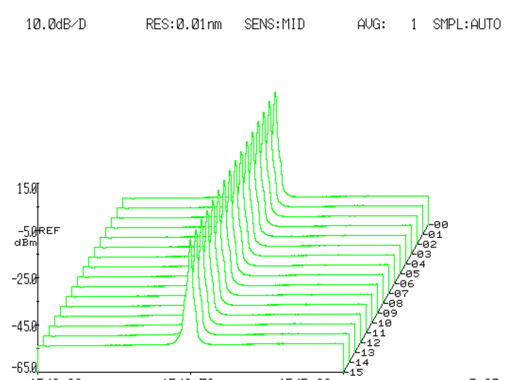

Fig. 11. The 16-time repeated scan of lasing spectra over 15 min.

4. Conclusion

A new kind of LMA EDF is designed and fabricated in our laboratory. Experimental results show that this method of manufacturing LMA EDF is feasible. The MFD of this fiber is 12.4 μm and 12.6 μm at 1550 nm according to Petermann-2 and Gaussian definitions, respectively. In addition, its cutoff wavelength is about 1176 nm, which makes the fiber can work in a single mode in the 1550 nm band. At last, the homemade LMA EDF is used to make a linear-cavity EDFL based on TFBG and OC. A stable lasing output with a 3-dB bandwidth of less than 0.03 nm, a power perturbation of less than 0.22dB and a wavelength shifts of less than 0.012 nm over 2h are achieved at room temperature.

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