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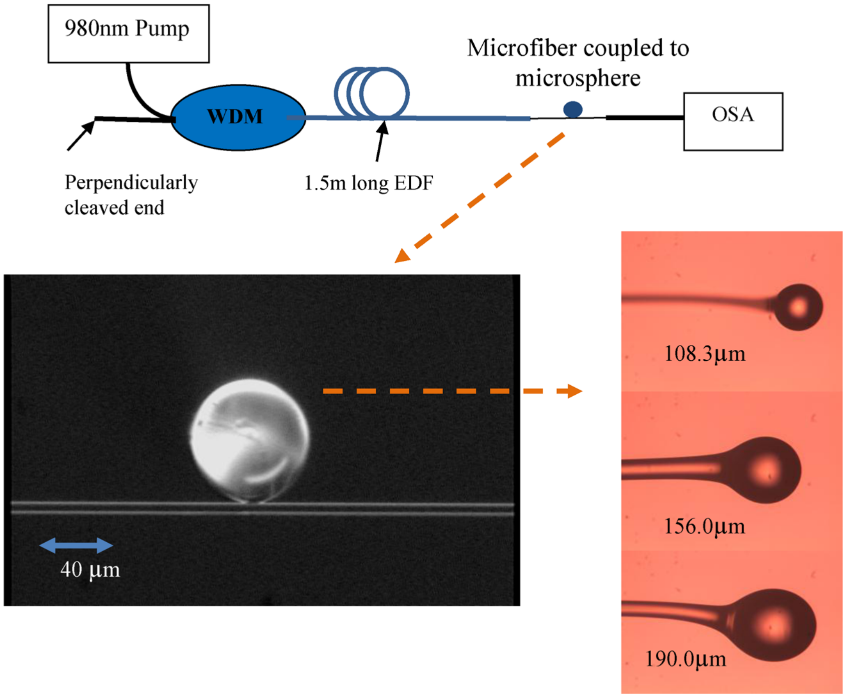

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Erbium-Doped Fiber Laser With a Microfiber Coupled to Silica Microsphere

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Abstract: A compact erbium-doped fiber laser (EDFL) is demonstrated using a piece of 1.5-m-long erbium-doped fiber (EDF) with a microfiber coupled to a silica microsphere at the output end. A stable laser output is achieved due to the recirculation of amplified spontaneous emission (ASE) light inside the linear cavity and the incorporation of microsphere which serves as both a laser filtering element and a mirror. The laser operates at 1533.5 nm with a peak power of 7.7 dBm and an optical signal-to-noise ratio (OSNR) of around 24.4 dB with 980 nm pumping of 100 mW and a sphere diameter of 137 μm. The operating wavelength can be tuned down from 1533.4 to 1531.24 nm by changing the sphere diameter from 108.3 to 190.0 μm. The highest Q-factor of 12760 is obtained at the smallest sphere diameter of 108.3 μm.

Index Terms: Tapered fiber, microsphere, erbium-doped fiber laser (EDFL).

1. Introduction

Miniaturization of optical elements has been fueled by the need to have very compact devices that are spatially and economically desirable for the telecommunications industry. This has stimulated the development of high-*Q* dielectric microcavities, in which light is trapped internally as whispering-gallery modes (WGMs) or simply optical resonances. In a dielectric microsphere, an optical WGM which consists of light propagating around the equator is spatially confined to a narrow beam near the sphere's surface by total internal reflection. The extremely low WGM losses of fused-silica microspheres allow them to be used as high-*Q* microresonators [1], [2]. Such microresonators have the potential to be used in many areas, including cavity quantum electrodynamics [2], microlasers [3], laser stabilization [4], nonlinear optics [5], and evanescent-wave sensing [6].

Of late, there is also a growing interest on ultracompact fiber lasers, which is attractive not only for integration but also for operation in single longitudinal mode. They can be constructed using a short length rare-earth doped fiber with high reflectivity dielectric mirrors deposited on the fiber facets to form a Fabry–Perot cavity [7]. Micro/nanoscale lasers are also recently demonstrated using semiconductor nanowire [8] and laser dye [9] as the gain medium. In our earlier work, a compact erbium-doped fiber laser (EDFL) is demonstrated using a highly concentrated erbium-doped fiber (EDF) as a gain medium in conjunction with microfiber knot resonator (MKR) at the end of the gain medium which functions as both reflector and tunable filter [10]. In this paper, a compact EDFL is

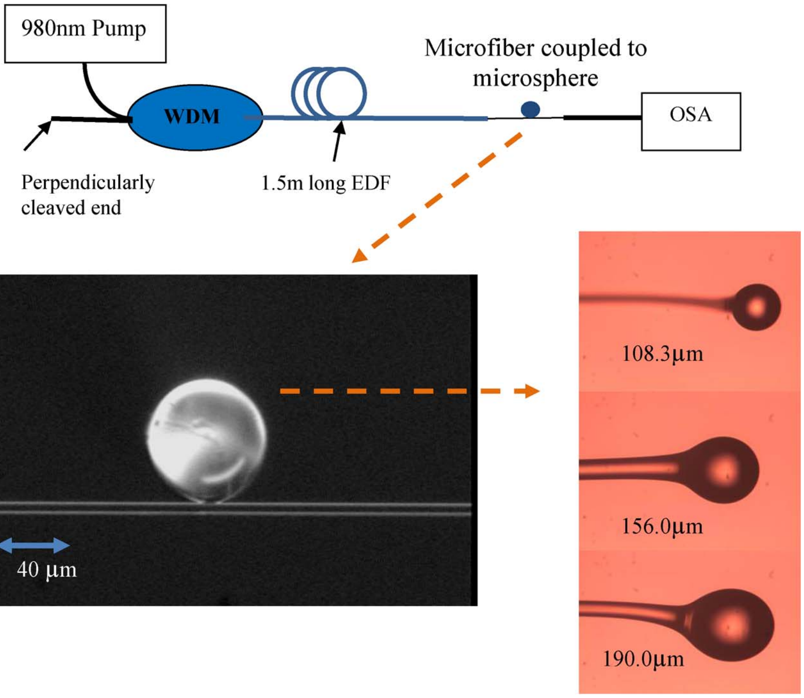

Fig. 1. Configuration of the proposed microsphere-based EDFL. Insets show the fabricated microsphere touching a microfiber and the fabricated spheres with three different diameters.

demonstrated using a piece of 1.5-m-long EDF with a microfiber coupled to a silica microsphere at the output end. The microsphere acts as both a wavelength selective filter and a reflector. The performance of the laser is investigated for various sphere diameters.

2. Experiment

A microsphere is fabricated from a standard single mode glass fiber, SMF-28, by an arcing technique using a fusion splicing machine. The material of the fiber core is a purified glass containing 99.999% of SiO2. The core is surrounded by the cladding, which is covered with polymer coating. The standard operation for microsphere formation on an optical fiber consists of three steps. First, in the fiber preparation process, a portion of the fiber is stripped off its coating using a fiber stripper. The bare fiber is wiped with cotton soaked with ethanol to remove coating chips from adhering to the fiber and then the fiber end surface is cleaved with a fiber cleaver. Secondly, in the fiber loading process, we open the windshield of the splicer, the fiber holders and the fiber clamps and load the prepared fiber into the left side of the holder with the stripped portion in the V-groove. It is important to make sure that the fiber is properly aligned in the V-groove before closing the fiber holder. The fiber clamp is closed afterward to hold the fiber on the V-groove. Once the fiber is loaded correctly, the windshield is closed and finally the formation of the microsphere starts with the arching process. After setting the arc power, the cleaning arc power offset and the cleaning time, the fabrication of the microsphere commences. The fiber tip absorbs the arc discharging heat and melts instantaneously. Due to the surface tension, the melting part of the fiber starts to form a spherical shaped tip gradually during solidification. As the spherical tip grows bigger, the effect of gravity force grows, pulling the tip toward the gravity field. This causes a drop of the spherical tip and increases the offset distance between the center of the sphere and the axis of the fiber stylus.

Fig. 1 shows the proposed microsphere-based EDFL, which consists of a piece of highly concentrated EDF with a microfiber coupled to the fabricated microsphere at one end of the fiber and wavelength division multiplexing (WDM) coupler at the other end. A 980 nm laser diode is used as a pump to generate the light injected into the EDF via the WDM coupler. The gain medium is a

1.5-m-long EDF with an erbium ion concentration of about 2000 ppm. A small section of the fiber end is stripped (about 3 cm long) and stretched to a waist diameter of about 4 μm via flame brushing technique. The microfiber and microsphere are placed in contact such that the observed lasing signal is optimized on an optical spectrum analyzer (OSA). In this overcoupled regime, some portion of the forward amplified spontaneous emission (ASE) is coupled into the microsphere to be filtered and reflected back into the system to oscillate in the laser resonator cavity and generates a laser. The resonator cavity is formed by this microsphere and a perpendicularly cleaved gain medium at the input end of the laser. Owing to the refractive index difference between silica glass and air, approximately 3–4% of light was reflected back into the cavity for laser oscillation.

Microspheres possess high Q-factor morphology-dependent resonances (MDRs). Its operation can be analyzed using a Maxwell's equation based description [11]. However, geometrical optics can also be used as a conceptually simplified way to explain the operation of this spherical resonator [12]. A physical interpretation of MDRs is based on the propagation of rays around the inside surface of the microsphere, confined by an almost total internal reflection [13], [14]. The rays approach the internal surface at an angle beyond the critical angle and are totally internally reflected each time. After propagating around the microsphere, the rays return to their respective entrance points exactly in phase and then follow the same path all over again without being attenuated by destructive interference. It takes longer for the energy of a MDR to leak out of the microsphere, and extremely large energy densities can accumulate in the MDR. MDR frequencies (or wavelengths) depend on the size, shape and refractive index of the microspheres. MDRs satisfy resonance conditions for specific values of the size parameter $x = 2\pi a/\lambda$, where a is the radius of the sphere and λ is the vacuum wavelength of light [15]. The spectral wavelength separation (mode spacing) between the adjacent MDR peaks is approximately given by

$$\Delta\lambda = \left(\lambda^2 \arctan(n-1)^{1/2}\right) \Big/ \left(2\pi a(n-1)^{1/2}\right) \tag{1}$$

where n is the refractive index of the microsphere with respect to the surrounding medium [16]. The Q-factor of a MDR is a measurement of the sharpness of the resonance peak and is defined as the time averaged stored energy per optical cycle over power loss. The quality factor, Q can be calculated from measurements of the resonant peak and the equation is given below [17], [18]

$$Q = \frac{\lambda}{\delta\lambda_{\mathrm{FWHM}}} \tag{2}$$

where $\delta\lambda_{\mathrm{FWHM}}$ is the width at full-width at half maximum power of the resonant peak. The free spectral range (FSR) of the MDR is related to the effective index of the mode, n_{eff} by [19]

$$FSR = \frac{\lambda^2}{2\pi n_{\mathrm{eff}} a}. \tag{3}$$

The output of the EDFL was tapped from the microfiber output end and characterized by an optical spectrum analyzer (OSA) with a resolution of 0.015 nm. The performance of the laser was investigated for various sphere diameters, which was varied from 100 to 230 μm.

3. Result and Discussion

The 980-nm pump light was launched into a 1.5-m-long EDF to generate an ASE in the 1550 nm region. The ASE oscillated in the linear cavity, which was formed between the microsphere and the perpendicularly cleaved fiber end at the opposite side to generate a laser. The microsphere operates as a wavelength selective device as well as a narrow band reflective mirror in the laser cavity. Due to the filtering characteristic of the microsphere, lasing action was observed for the EDFL with sphere diameters within 100 to 230 μm. A typical output spectrum of the EDFL, with pump power of 100 mW and sphere diameter of 137 μm, is shown in Fig. 2. It operates at 1533.5 nm with the peak power of 7.7 dBm and an optical signal-to noise ratio (OSNR) of around 24.4 dB. It is also observed in Fig. 2 that there is no lasing without the microsphere. The ASE power is also slightly reduced after the

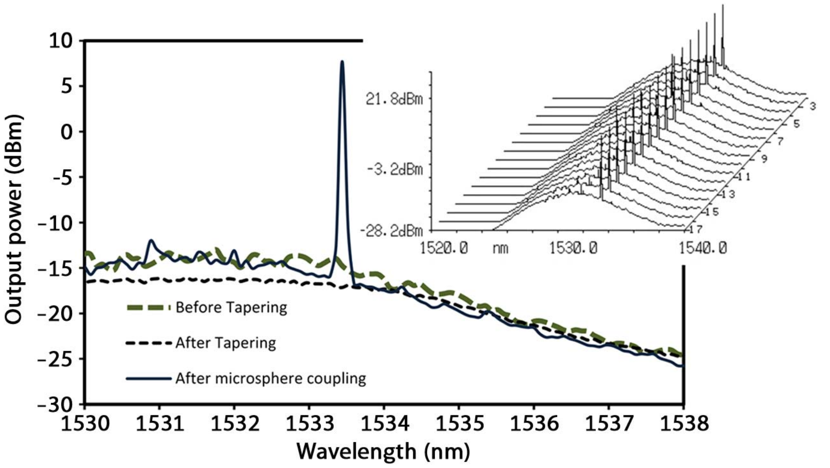

Fig. 2. Output spectra of the EDFL configured with and without microsphere coupling. The microsphere has a diameter of 108.3 μm. (Inset) Spectrum evolution of the proposed laser, which was recorded for scanning in every 10 min.

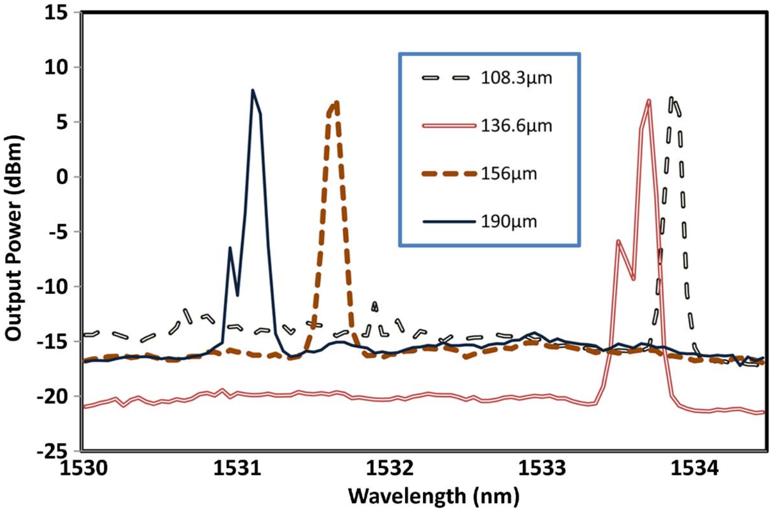

Fig. 3. Output spectrum of the proposed laser at different sphere diameters.

tapering due to the loss at the transition regions. The operating wavelength of the proposed microsphere-based laser is dependent on the resonance wavelength of the MDR. The optical lasing is obtained due to the recirculation of the ASE light inside the linear cavity and the incorporation of microsphere which serves both as a laser filtering element and a mirror. The resonant wavelength of a microsphere is determined by the refractive index of the microsphere, sphere dimensions, tapered fiber dimensions and relative positions of the components and differences in propagation constants between the two fibers. Some of these parameters are dependent on temperature and strain, therefore the resonant wavelength of the microsphere can be tuned by varying these quantities. The inset of Fig. 2 shows the spectral evolution of the output peak recorded in every 10 minutes, which indicates the stability of the laser. The small variations of wavelength and output power are observed, which are mainly attributable to the fluctuation of the 980 nm pump power and the temperature variance.

Fig. 3 shows the lasing spectrum at different sphere diameters. As shown in Fig. 3, the peak wavelength of the laser shifts to a shorter wavelength when the sphere diameter increases. For instance, the peak wavelength can be tuned from 1533.4 nm to 1531.24 nm as the sphere diameter

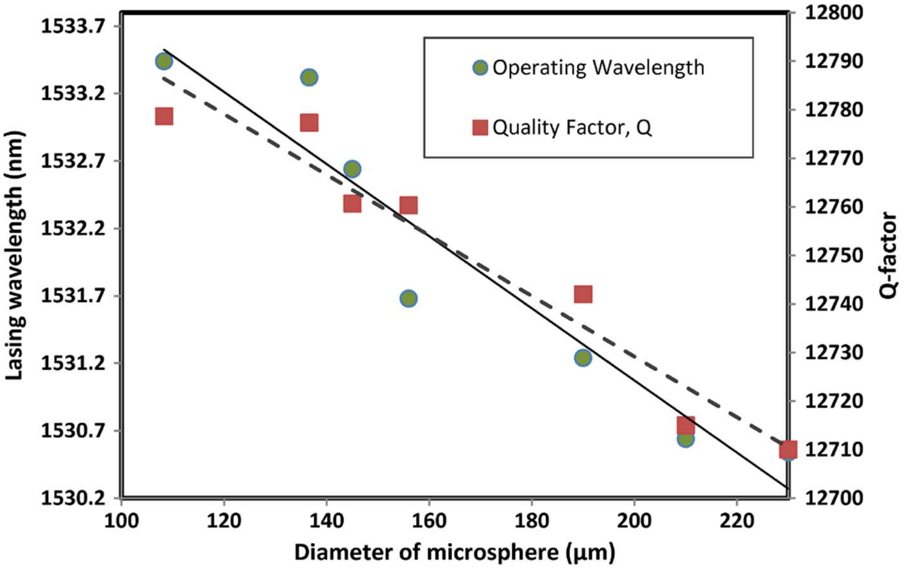

Fig. 4. Shift of the laser's operating wavelength and Q-factor against the microsphere diameter.

is increased from 108.3 μm to 190.0 μm. This is attributed to the FSR of the MDR, which increases as the diameter decreases as shown in (3). It is also observed that the OSNR is maintained above 24 dB with the variation of sphere diameter. Fig. 4 shows plots of operating laser wavelength and *Q*-factor against the sphere diameters. The *Q*-factor of silica microsphere was calculated from (2), and the highest *Q*-factor of 12,760 is obtained at the smallest sphere diameter of 108.3 μm. As seen in Fig. 4, the wavelength of the lasing peak is linearly shifted to a shorter wavelength as the sphere diameter increases with a slope coefficient of -26.8 pm/μm. The quality factor *Q* also linearly degrades as the sphere diameter increases at the rate of $-0.62/\mu$m. Other factors which may affect the quality of the output laser include the loss due to the surface roughness and the overall shape of the microsphere. Quantitative effects of these factors require further investigation and analysis. It is also experimentally observed that if the coupling is properly maintained between the microsphere and microfiber, the lasing wavelength is unchanged regardless of the position of the microsphere along the microfiber.

4. Conclusion

A compact single-wavelength fiber laser is demonstrated using a 1.5-m-long EDF where its end section is tapered and coupled with a fabricated microsphere that acts as a wavelength selective filter as well as a reflector. A stable laser output is achieved at 1533.5 nm with a peak power of 7.7 dBm and an OSNR of around 24.4 dB using a 980-nm pump at 100 mW power when the microsphere diameter is fixed at 137 μm. The operating wavelength shifts down from 1533.4 nm to 1531.24 nm as the sphere diameter increases from 108.3 μm to 190.0 μm. The highest *Q*-factor of 12 760 is obtained at the smallest sphere diameter of 108.3 μm.

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