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Tunable fiber laser with nano-thick silver diaphragm as compound external cavity

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ABSTRACT

An optimized tunable fiber laser has been proposed by using a novelty developed silver diaphragm at the end of coupled cavity of the tunable fiber laser. The total tuning range is about 15 nm by using a combination of axial compressive strain and a tensile strain. The lasing mode regime of tunable fiber laser is determined by the fiber laser compound cavity. Experimental results demonstrate that the characteristics of tunable fiber laser with external cavity not only present good stability performances with the output power variation about 0.2 dB and the wavelength fluctuation less than 0.08 nm, but also could reduce threshold pump power, decrease the linewidth from 19.557 kHz to 7.271 kHz by coupling silver membrane at the end of the fiber truncation. The optimized tunable fiber laser of external cavity configuration is in good agreement with the theoretical analysis and has many potential applications in sensing and communication system for high sensitivity and remote measurement.

1. Introduction

As tunable fiber lasers [1,2] are fully compatible with existing fiber devices in telecommunications and optical sensors by fused couplers, polarizers, filters and phase modulator and consequently envisioned a new all-fiber laser technology. Several tunable fiber lasers with different tunable devices have recently been reported, such as acousto-optical filters [3], a tunable fiber Fabry-Perot filter and bandpass filters [4], and polarization of low-beat noise [5]. Each of these methods has its own features and advantages in different application fields. However, considering the drawbacks of complex structure, high cost and large volume, people have tried to select the fiber Bragg grating (FBG) as the candidates because of its sharp spectral filtering characteristics, low insertion loss and cost. Nowadays, a number of techniques have been proposed and demonstrated to achieve widely tunable filters for fiber lasers using FBG [6]. In terms of the FBG, it is widely used as mirrors for fiber lasers, as temperature, stress or pressure fiber sensors in engineering, as filters, mode converters or wavelength

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multiplexers in telecommunications. To achieve the FBG central wavelength peak shift the main method is to change the grating period by induced thermally or mechanical stresses. In the case of the mechanical stresses applied to the FBG, a number of techniques have been proposed and demonstrated in the article [7,8], and most of them are based on the beam bending technique through compressing or stretching of the FBG. A wavelength shift as large as 35 nm has been reported by this method [9]. However, it required special material, complicated and bulky components to perform the tuning action.

Recently, multi-methods of rare-earth doped fiber lasers have been reported by several researchers. Nevertheless, most of the researchers focus on the Er^{3+} doped fiber lasers [10–12]. Compared to the Er^{3+} doped fiber (EDF), Er^{3+}-Yb^{3+} codoped fiber (EYDF) can be used to suppress the self-pulsing of Er^{3+} ions and avoid the serious degradation of gain and pump efficiency even for higher Er^{3+} ions concentration. On the other hand, the Ytterbium sensitization offers more efficient pump absorption over broader absorption band, thus allowing short laser cavity construction of EYDF fiber lasers critical for mode-hop free and output power stability of the fiber laser. At the same time, the low ratio of photon to fluorescence lifetime in linearity fiber laser ensures the higher sensitivity and longer measurement range in the optical sensor measurement system compared to fiber ring laser and laser diode [13–15].

In this paper, we propose a wavelength tunable fiber laser in EYDF with external cavity feedback (LECF) by silver membrane butt-coupled on the truncation of bare fiber. The wavelength tuning is achieved by using a combination of axial compression and tension of FBG which is caused by compress or stretch the ceramic ferrules where the ends of FBG were glued into the ceramic ferrules. Typically, the fiber strength associated with tensile stress is limited because silica is 23 times stronger under compression than under tension. The tunable range of the fiber laser in this paper is about 10 nm in the compressive mode and 5 nm in the tensile mode. In addition, the compound-cavity of fiber laser consisting of external cavity and inner cavity determines the lasing mode regime of LECF. The main advantages are the enhancement of single longitudinal mode operation, the spectral line-narrowing, the improved frequency stability, lowing threshold pump and also its simple, compact, robust structure. The influence of external optical feedback results from the coherent nature of the optical feedback.

2. Theoretical analysis

To tune the Bragg grating central wavelength peak, mechanical stresses have been applied to the optical fiber. In particular, the tuning range is directly proportional to the fiber Bragg grating strain. According to the article [16], the Bragg central wavelength shift $\Delta\lambda$ is given as follows

$$\frac{\Delta\lambda}{\lambda} = (1 - \mathrm{p_e}) \cdot \varepsilon \tag{1}$$

where λ is the Bragg grating central wavelength peak in an unstrained condition, $\mathrm{p_e} = 0.21$ is the photo-elastic coefficient, and ε denotes the axial strain which is defined by

$$\varepsilon = \frac{\Delta L}{L} \tag{2}$$

where ΔL is the axial displacement and L is the unstressed length. In addition, the lateral strain perpendicular to the fiber axis is neglected since it is much less than the axial strain.

Moreover, in order to study the effect of the external cavity in the tunable fiber laser, we calculate and get the formulas about the change of threshold gain and linewidth based on the steady-state amplitude and phase equations of lasing condition in the three-mirror model as follows [17,18]:

$$\Delta \mathrm{g} = \frac{\xi}{L_{in}} \cos(2\pi\nu\tau_e) \tag{3}$$

$$\delta\nu = \frac{\delta\nu_0}{(1 + C\sin(2\pi\nu\tau_e + \arctan\alpha))^2} \tag{4}$$

Where $\Delta\mathrm{g}$ and $\delta\nu$ represent the changes of threshold gain and laser linewidth with feedback respectively. $\delta\nu_0$, α and τ_e($= 2L_{ext}/c$,where L_{ext} and c represent the length of external cavity and the speed of light respectively) are the laser linewidth without external cavity, linewidth enhancement factor and the time of a round-trip through external cavity respectively. $\xi$and C refer to related external cavity coupling coefficient and feedback strength parameter. According to Eqs. (3) and (4), it is evident that the changes of threshold gain and laser linewidth are repetitive function of τ_e. So, a Piezoelectric Transducer (PZT) under a suitable driving voltage is used in the external cavity to obtain the optimized value of L_{ext}.

3. Experimental setup

Based on the theoretical analysis, we set up the experimental system of LECF based on nano-thick silver diaphragm as compound external cavity, as shown in Fig. 1. The configuration consists of a segment of EYDF pumped by a 980-nm pump laser, a wavelength division multiplexer (WDM), a 2*2 optical coupler with couple ratio 50:50, and a fiber Bragg Grating (FBG) fixed in a tunable unit. The Fabry–Pérot cavity fiber laser incorporates a short length of EYDF with a pair of reflectors that one is a FBG to select the lasing wavelength and the other is an optical fiber mirror with two output ports of a coupler

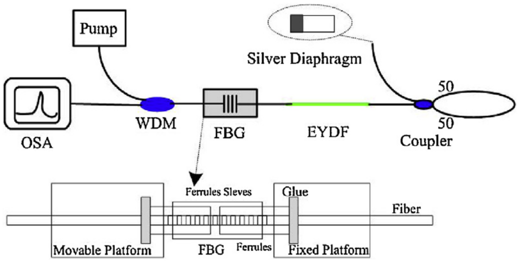


Fig. 1. Experiment setup of LECF based on nano-thick silver diaphragm.

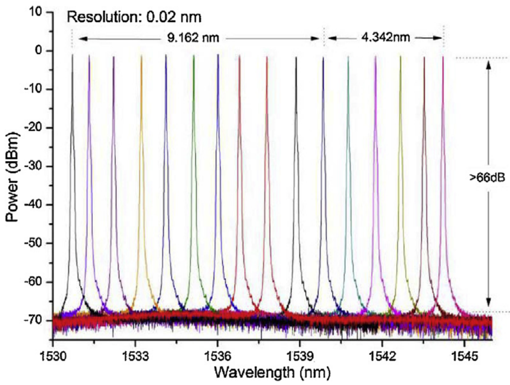


Fig. 2. The measured output power spectrum over the tunable range with the minimum resolution of OSA 0.02 nm.

fused together. The WDM is applied to launch the pump power into the EYDF. The stimulated gain medium (EYDF) amplifies the signals of λ chosen by the mode selecting apparatus of FBG with Bragg wavelength of 1539.87 nm without strain at room temperature, which could be observed by the optical spectrum instrument (OSA) (AQ6370C,Yokogawa). The bandwidth and grating diffraction efficiency reflectance of FBG are 0.285 nm and 89% respectively. The tunable unit consists of two stages mounted on the base plate, two ceramic ferrules and one ceramic bushing. One of the stages can provide axial movement through a micrometer head to accurately achieve the compression or tension of FBG. Moreover, the ceramic ferrules fixed to the optical fiber are 10 mm long with the external and internal diameters of 2.5 mm and 127 um respectively which are used to facilitate both compression and tension of FBG. In addition, the ceramic bushings are used to carefully align the ferrules to avoid extra bending of the FBG. In this case longitudinal mode hopping is eliminated since the change in cavity resonance wavelength tracks the change of Bragg reflector. To optimize the feedback strength parameter, silver is selected as an external reflector because of its outstanding advantages, such as good stability and the reflectivity of the diaphragm is at the scope controlling from 10% to 90% within the near and intermediate infrared range of light. Thus, the external cavity is introduced with a nano-thick silver diaphragm butt-coupled at the other port of coupler. In this case, the electroless plating method in a silver–ammonia solution is to fabricate the butt-coupled silver diaphragm on the truncation of bare fiber [19,20]. Compared to other diaphragm fabrication technologies, such as the magnetron sputtering vacuum coating method or the pulsed laser deposition coating method, the electroless plating method is more convenient, less costly and relatively simple process while the diaphragm thickness can be precisely generated at a uniform of hundreds nanometers. Therefore the optimized output signal derived from the compound-cavity mode in tunable wavelength fiber laser is characterized using a variety of techniques, described in the following sections.

4. Experimental results

By precisely adjusting the strain, the laser can oscillate with different wavelengths at room temperature. Fig. 2 shows the laser spectrum of LECF with the reflectivity of silver diaphragm at 64.8%, which is obtained with pump power of 34.6 mW. The entire tuning range is about 15 nm and the signal-to-noise ratio (SNR) is about 70 dB which is larger than EDF laser due to the Yb^{3+} ion sensitization. The center wavelength continuously tuning range from 1539.87 nm to 1530.708 nm in the compression mode is greater than that of tension mode with the tuning range from 1539.87 nm to 1544.212 nm, which also confirms the fact that the silica fiber is 23 times stronger in a compression mode than in a tension mode. The output power performance of the laser system with different wavelengths is presented in Fig. 3. The results show that the output power maximum fluctuation of the laser over the whole tunable range is about 0.8 dB with the pump power of 34.6 mW.

Fig. 4 illustrates the simulated and experimental values of central wavelength of FBG along with variation of displacement which is achieved in 10 μm intervals. As shown in red dot, the central wavelength shift of FBG is also in proportional to the

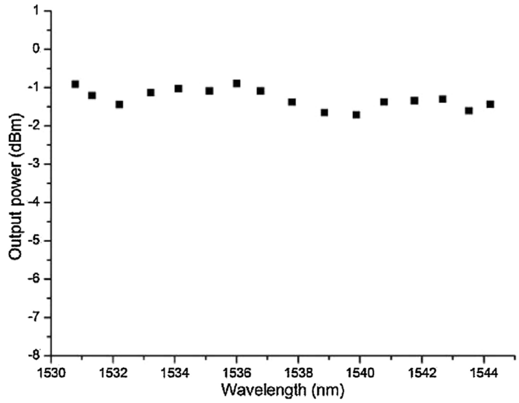


Fig. 3. Fluctuation of the laser output power over the whole tunable rang with pump power of 34.6 mW.

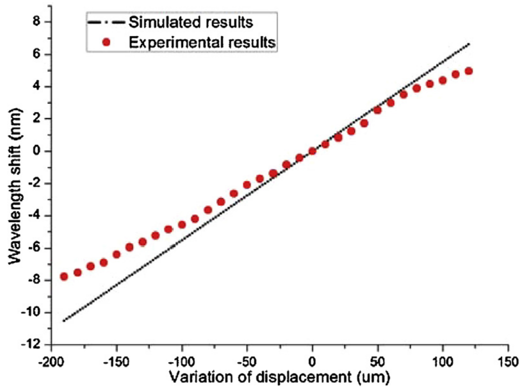


Fig. 4. The experimental values of central wavelength along with variation of displacement.

variation of displacement which is agreement with the theoretical analysis. According to Eqs. (1) and (2), we simulate and get the relationship between wavelength shift and variation of displacement of FBG with $\lambda = 1539.87$nm and $L = 22$mm. The wavelength shift of FBG is proportional to the variation of displacement. When the tension is applied on the FBG, the central wavelength drifts towards to the direction of larger valves, on the contrary, the central wavelength shifts towards to the opposite direction accordingly. However, compared with the values of simulation in dotted black line, the central wavelength shift is smaller with the same variation of displacement. For example, the experimental and simulative values of central wavelength shift are 4.383 nm and 5.53 nm respectively with the same variation of displacement 100 μm. To our best knowledge, the main reason is that the relative motion at the fixed points between the fiber and the glue will happen. In addition, the displacement measurement by micrometer is also not precise enough.

In the tuning experiments, we also studied the stability performances of LECF in terms of power variation and wavelength drift. Fig. 5 illustrates the output spectra monitored continuously for more than one hour at three minutes interval with the lasing wavelength at 1537.02 nm. The experiments are carried out in the laboratory environment. The results that the output power variation is only about 0.2 dB and the wavelength fluctuation is less than 0.08 nm which is limited by the OSA's resolution over the entire period of measurement time show good laser stability.

To confirm the reduction of gain at threshold caused by an external cavity feedback in the fiber laser, we studied the relationship between output power and pump power with or without external cavity feedback respectively, as shown in Fig. 6. The red triangle dots are the output power with respect to pump power without external cavity feedback and the black square dots denote the output power with respect to pump power with external cavity feedback coefficient of 64.8%. According to Fig. 6, the output power of LECF is larger than the fiber laser without external cavity feedback when the pump power is less than 90 mW. However, both of them are almost equal following the pump power larger than 90 mW. It is worth mentioning that the reflected light from the silver diaphragm not only contains the signal light, but also the pump light considering the wider feedback bandwidth of silver diaphragm including the near and intermediate infrared range. Then it is not difficult to understand that the output power with external cavity feedback is larger than that without external cavity feedback when the pump power is lower, which is because the pump light re-enters the laser cavity through the external cavity feedback and is amplified by the segment of EYDF again to enhance the conversion efficiency. In other words, the external cavity feedback acts as backward pump. In the other situation, the output power is limited by the doping concentration and absorption efficiency when the pump power is higher based on our analysis. In addition, the gain factor

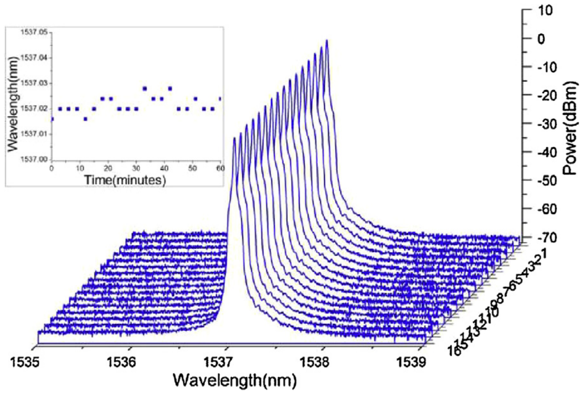


Fig. 5. Optical spectra of LECF monitored at 3 min interval (inset: stability of the oscillation wavelength over an hour).

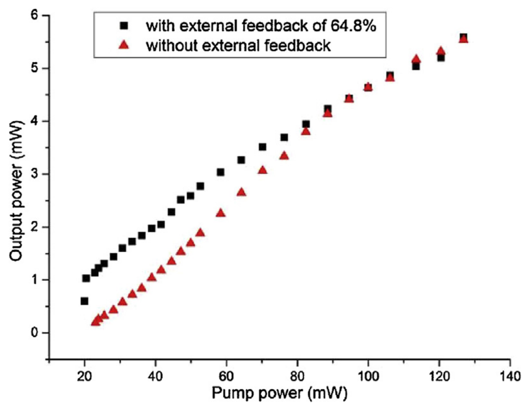


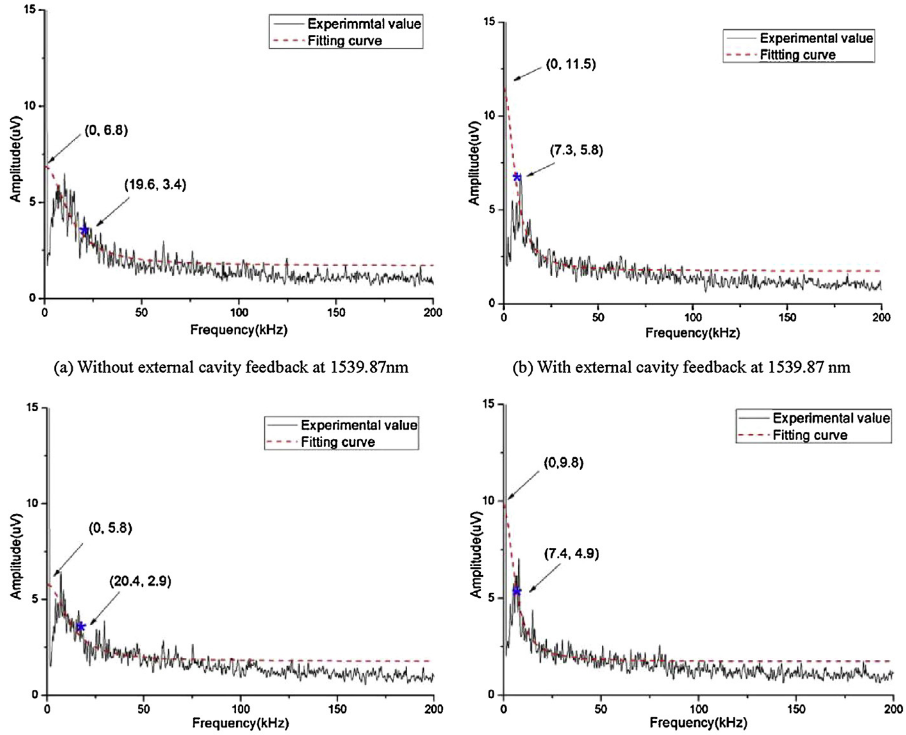
Fig. 6. The relationship of output power and pump power with or without external cavity feedback. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

increases along with incident light intensity when the incident light intensity is lower. However, the gain factor tends to saturation when the incident light intensity increases to a certain extent. As is known to all, EYDF relys on indirect pumping of the lasing Er^{3+} ions through non-radiative energy was transfered from the Yb^{3+} ions. The Er^{3+}/Yb^{3+} ions concentration will restrict the transition efficiency and the population inversion of upper level as the pump power is higher. What's more, the higher incident light intensity will reduce the population inversion of upper level resulting in the gain factor decrease. So we can assume that the influences of laser output power caused by the increase of pump power from external cavity feedback and the decrease of gain factor offset each other. In general, the threshold pump power of LECF is less than the fiber laser without external cavity feedback according to Fig. 6 which is in good agreement with the previous theoretical analysis.

As a further proof to discuss the effect of the external cavity feedback, the spectral linewidth of the tunable fiber laser is investigated by a homodyne technique using a fiber Mach–Zehnder interferometer with a 20 km delay-line in one arm. The bat signal generated by the interferometer, which is detected by a spectrum analyzer (Tektronix RSA-3408 B Real-Time Spectrum Analyzer) fed through a photo-receiver, is shown in Fig. 7. The descent at low frequencies is caused by the low-frequency filter in the photo receiver. Fig. 7(a) and (b) represents the spectral linewidth of fiber laser without or with external cavity feedback at 1539.87 nm, respectively. Similarly, Fig. 7(c) and (d) illustrates the spectral linewidth of fiber laser without or with external cavity feedback at 1537.02 nm, respectively. Lorentzian approximation curve fittings used to evaluate the measured value are shown in Fig. 7 by the red dotted lines. As shown in Fig. 7, the linewidth of the fiber laser with external cavity feedback is 7.3 kHz while the linewidth of fiber laser without external cavity feedback is 19.5 kHz at 1539.87 nm. As is known to all, the linewidth of 10 kHz corresponds to a coherence length of 30 km, which is larger than the delay-line length. Therefore, the actual linewidth of the laser output is less than the measured values. It is indicated that the employment of external cavity would guarantee the narrow linewidth operation which has many potential applications in sensing and communication system for high sensitivity and remote measurement.

5. Conclusion

We demonstrate a compact configuration of tunable fiber laser with a nano-thick silver diaphragm as external cavity which is first proposed in the literature. The lasing mode regime of LECF is on account for the compound-cavity mode selection



(a) Without external cavity feedback at 1539.87nm (b) With external cavity feedback at 1539.87 nm

(c) Without external cavity feedback at 1537.02nm (d) With external cavity feedback at 1537.02 nm

Fig. 7. The homodyne signal of fiber laser measured with 20 km delay-line and theoretical Lorentzian approximation (red dotted line). (For interpretation of the references to color in the text and this figure legend, the reader is referred to the web version of this article.)

system which is up to the interaction of fiber laser mode and external cavity mode. The silver diaphragm is used to reflect the lasing light into the fiber laser intracavity functioned as the external cavity of the fiber laser. The electroless plating method of silver diaphragm is convenient and low cost in production process. In our experiment, the total tuning range is about 15 nm by using a combination of axial compressive strain and a tensile strain. Furthermore, the fiber laser with feedback not only presents good stability performances with the output power variation about 0.2 dB and the wavelength fluctuation less than 0.08 nm, but also has a good SNR about 70 dB, reduces the threshold pump power and decreases the linewidth from 19.557 kHz to 7.271 kHz. The optimized tunable fiber laser of external cavity configuration is in good agreement with the theoretical analysis and these properties are important to the sensing application and communication system.

Acknowledgements

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