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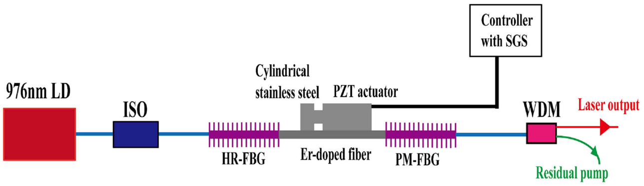

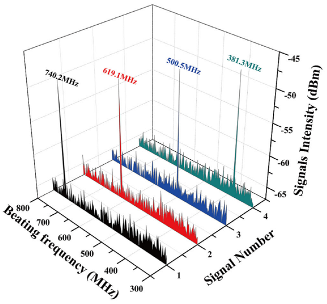

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Ultrafine Frequency Linearly Tunable Single-Frequency Fiber Laser Based on Intracavity Active Tuning

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Abstract: An ultrafine frequency linearly tunable single-frequency fiber laser based on the intracavity active tuning is demonstrated. Single-frequency operation can be achieved by an ultrashort cavity and ultranarrow polarization-maintaining fiber Bragg grating. A sub-nanometer-accuracy piezoelectric ceramic actuator with closed-loop mode has been employed to realize the cavity-length active tuning scheme, which can achieve a linear tuning range of $>$1 GHz with a 3.2-MHz/nm tuning resolution. The periodic tuning repeatability and repeat accuracy show that the scheme can realize linear frequency tuning with great tuning repeatability and high tuning precision.

Index Terms: Ultrafine, linearly tunable, fiber laser.

1. Introduction

Tunable single-frequency fiber lasers have the characteristics of adjustable wavelength, narrow linewidth, high service life, and good compatibility with fiber communication system [1]–[5], and have become key devices in all-optical networks to realize the functions of all-optical wavelength conversion (AOWC), optical cross-connect (OXC), and optical add/drop multiplexers (OADMs) [6]–[9]. Tunable fiber lasers are of considerable interest for many applications, such as lidar [10], [11], laser remote sensing [12], and spectral measurement analysis [13], [14].

Fiber Bragg grating (FBG)-based stress tuning schemes have now been commercialized, which uses piezoelectric ceramics (PZTs) to apply axial stress on the FBG [15], [16]. However, at present, the optical fiber grating and the fusion point with the active fiber are also easily affected by stress change. The basic optical characteristic of an FBG is a narrow-band optical filter centered on the Bragg resonance wavelength, which only reflects the light of the Bragg central wavelength [17], [18]. Owing to the uncertainty modulation effect on the center wavelength, bandwidth, and reflectivity of the gratings, it is rather difficult or even impossible to achieve a linearly modulated single-frequency laser source [19]. In addition, the optical transmission systems need more laser

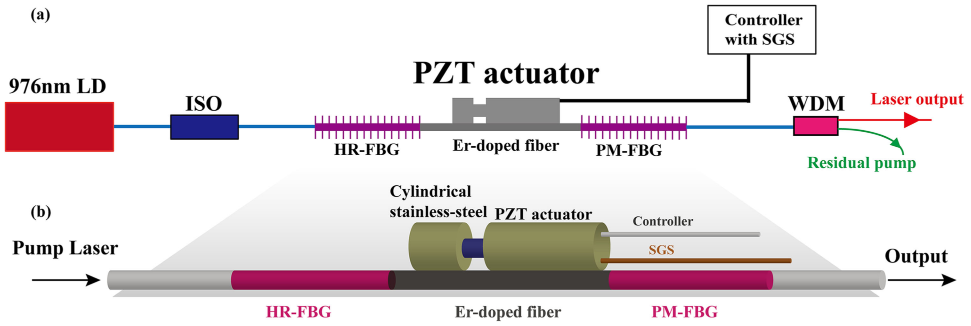

Fig. 1. (a) Schematic of experimental tunable single-frequency fiber laser and (b) drawing of partial enlargement of laser cavity with PZT module.

channels and higher laser capacity to meet the ever-increasing data transmission, which demands higher-frequency tuning fineness for tuning fiber lasers.

In this paper, we experimentally demonstrate an ultrafine-frequency linearly modulated single-frequency fiber laser with an ultrashort cavity length of 9.5 cm. A high-gain phosphate fiber acts as the active fiber, which delivers high power with a short cavity. A PZT actuator with a strain gauge sensor (SGS) is bonded with the active fiber, which can realize closed-loop operation to accurately modulate the cavity length. As a result, single-frequency operation can be possibly achieved by the short laser cavity and an ultranarrow bandwidth (0.02 nm) of a polarization-maintaining FBG (PM-FBG) as stable laser oscillation is established in a very short time. A maximum modulating range of $>$1 GHz is achieved with an average tuning step of 3.2 MHz/nm. The laser has very stable frequency linear tuning over the entire tuning range, showing excellent repeatability and periodicity.

2. Experimental Details

The experimental setup with a schematic representation of the proposed single-frequency fiber laser configuration is depicted in Fig. 1(a). The laser cavity is constructed by a pair of an ultranarrow band PM-FBGs (5.7 cm) and a broadband high-reflection (HR) FBG, which are fused by splicing with a 1.7-cm-long highly Er3$+$-doped phosphate fiber fabricated and developed by NP Photonics. The lengths of the PM-FBG and HR-FBG are 5.7 cm and 2.1 cm. Single-frequency operation can be implemented by the short cavity of the laser and the ultranarrow bandwidth of the PM-FBG effectively. Corresponding to two linear polarization states of the PM-FBG fabricated on a PM optical fiber, the wavelength separation between the two PM peaks is larger than the 0.29-nm bandwidth of the HR FBG, leading to single-frequency operation simultaneously. A fiber-coupled 976-nm laser diode (LD) pump source was spliced to the input port of the optical isolator (ISO). The output of the laser cavity is coupled to the 980-/1550-nm wavelength division multiplexer (WDM) to split the residual pump and the laser.

The entire laser cavity is embedded in a heat sink with a high-resolution temperature controller in a sealed, seismically insulated structure to achieve and maintain low-noise single-frequency operation. A cylindrical PZT actuator (P-841.20) purchased from Physik Instrumente Co., Ltd is mounted with special adhesive on the middle of the active phosphate fiber, which provides sub-millisecond response and sub-nanometer resolution (0.3 nm) and is equipped with highly reliable multilayer piezo-ceramic stacks. The diameter and the length of the actuator is 12 mm and 50 mm, respectively. The maximum travel at closed-loop is 30 μm. Then, a cylindrical stainless-steel block with the same diameter as the PZT actuator is fixed to the multilayer piezo-ceramic stacks. The PZT actuator integrated with HR SGSs provides high precision for closed-loop operation. Fig. 1(b) shows an enlarged drawing of part of the laser cavity with the PZT module.

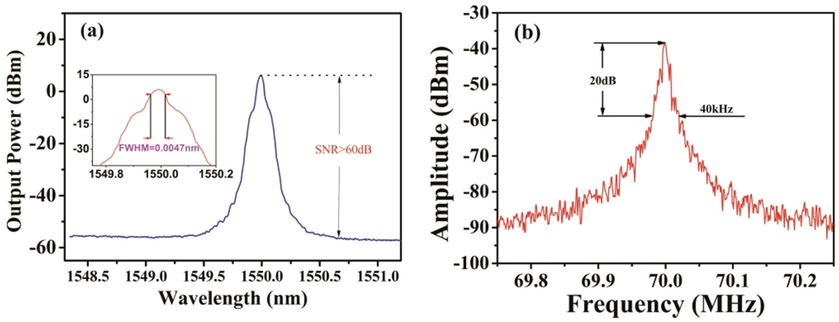

Fig. 2. (a) Output spectrum of 1550-nm single-frequency tunning fiber laser and (b) measurement result of delayed self-heterodyne interferometry for laser.

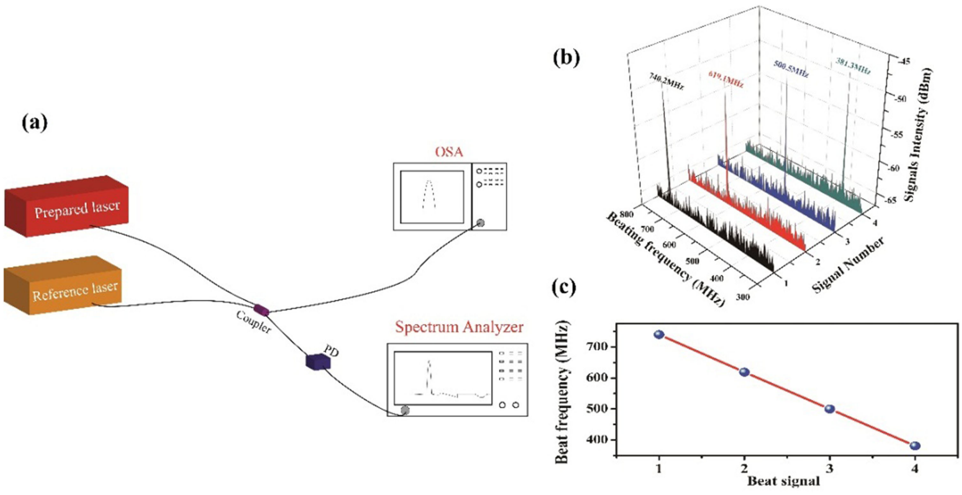

Fig. 3. (a) Laser beat frequency measuring system for measuring frequency tuning and (b, c) beat frequency variation from cavity-length variation at a tuning step of 40 nm.

3. Results

The output spectrum of the laser operating at 162.5 mW was measured by an optical spectrum analyzer (OSA, Agilent AQ6375) as shown in Fig. 2(a). Obviously, this single-frequency fiber laser has a signal-to-noise ratio of more than 60 dB. The inset shows the partially enlarged spectrum of the laser at 1549.99 nm. The fitting full width at half-maximum of the laser is obtained by the fitting to be 0.0047 nm, which is approach to the minimum resolution (0.005 nm) of the OSA. Therefore, the method of delayed self-heterodyne interferometry with a 50-km delay line was adopted to measure the linewidth of the laser, and the result is shown in Fig. 2(b). The 20 dB bandwidth of the beat signal is measured to be 40 kHz, which indicates that the measured laser linewidth is approximately 2 kHz.

The resonant frequency variation caused by cavity length is approximately several MHz, which exceeds the measuring limitation of the OSA. So, the laser beat frequency measuring system is used to detect the frequency tuning, as shown in Fig. 3(a). The reference laser was purchased from NKT Photonics (KOHERAS ADJUSTIK E15), which has better frequency stability than the prepared laser. The outputs of the two lasers were connected with couplers and simultaneously imported to the photoelectric detector. Labview software was programmed to monitor the spectrum analyzer in real time and simultaneously sample the frequency signals. The beat frequency signals of the two lasers vary with the variation of the cavity length at a tuning step of 40 nm, as shown in Fig. 3(b).

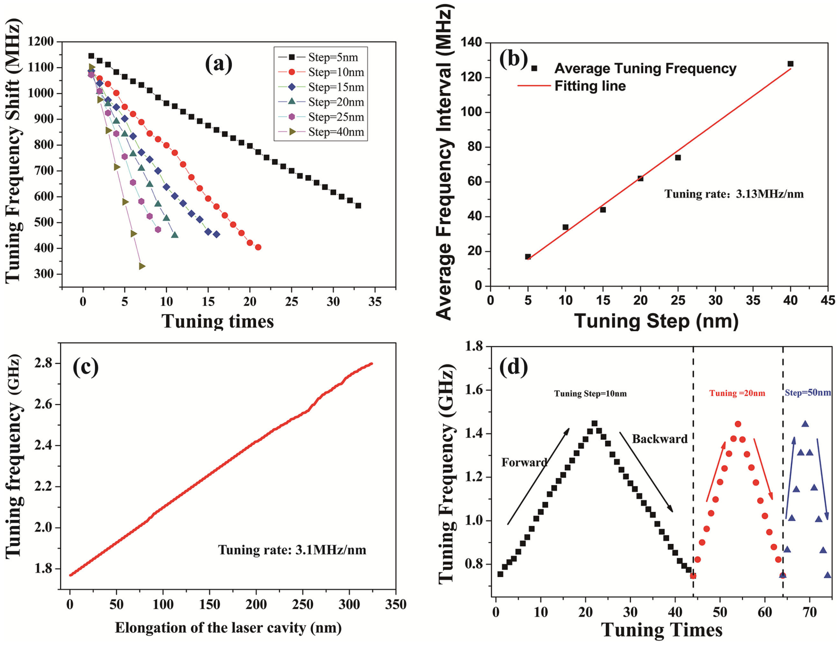

Fig. 4. (a) Tuning frequency shift and (b) average tuning frequency under different tuning steps; (c) tuning frequency range with elongation; (d) forward and backward tuning under different tuning steps.

The laser beat frequency signal shifts from 740.2 to 381 MHz under a total cavity-length change of 120 nm. Fig. 3(c) shows that there is a linear relationship between the expansion of PZT and the beat frequency shift, which, in turn, shows that the modulation frequency rate obtained by the cavity-length active-tuning method is approximately 3 MHz/nm.

Fig. 4(a) shows the beating frequency shift under different tuning steps. It can be clearly seen that under different tuning steps, the beating frequency decreases as the laser cavity length increases. The frequency reduction is basically in a linear relationship with the tuning step or the elongation of the laser cavity length, which is the same for all tuning steps. Therefore, linear tuning can be achieved with this scheme. In addition, the larger elongation of the laser cavity length can cause larger frequency shift, as shown in Fig. 4(b). By comparing the average beating frequency shift under different tuning steps, it is found that the average beating frequency shift has a linear relationship with the tuning step length. According to the fitting calculation, the laser frequency tuning rate is approximately 3.13 MHz/nm, which means that frequency linear tuning can be achieved, and the tuning step rate is controllable. The tuning frequency range of the laser with elongation is plotted in Fig. 4(c). The tuning frequency range of the laser is from 1.7 to 2.8 GHz, which basically maintains the linear relationship with elongation. After calculation, the tuning rate of the laser is approximately 3.1 MHz/nm, which indicates that the tuning rate remains unchanged during the entire tuning process. Therefore, by actively changing the length of the active Er-doped fiber in the laser cavity, laser-frequency-controllable linear tuning can be realized with a tuning range of more than 1 GHz.

The repeatability of frequency tuning is investigated by double-direction tuning under different tuning steps (10, 20, and 50 nm), shown in Fig. 4(d). The tuning frequency starts from 0.75 GHz, is forwardly tuned to 1.4 GHz, and then is reversely tuned back to 0.75 GHz with a synchronous step length. During the entire process, the tuning frequency and tuning step length remain basically linear. The frequency is also linearly related to the elongation from a double direction (forward and backward), and the result shows the uniformity between the corresponding tuning frequency rate and different tuning steps, which demonstrates that this linearly tunable fiber laser has satisfactory repeatability.

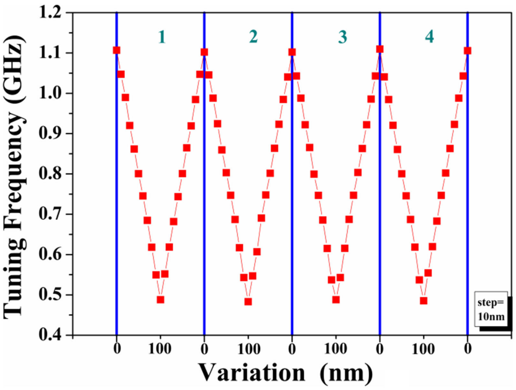

Fig. 5. Repeatability and repeat accuracy during the periodic tuning process.

The repeat accuracy during the periodic tuning process was studied, and the results are shown in Fig. 5. The periodicity of the frequency tuning is well maintained, and the tuning frequency under the same elongation is basically the same. The deviations of the tuning frequency under the same elongation are not significant in each cycle, and the tuning accuracy can reach approximately 0.3%. Therefore, this scheme can realize periodic frequency tuning with great tuning repeatability and high tuning precision.

4. Conclusions

A novel ultrafine frequency linearly tunable single-frequency fiber laser based on the intercavity active tuning is demonstrated. A closed-loop control PZT actuator with ultrahigh precision is employed to achieve the intracavity active tuning scheme. Single frequency operation can be confirmed by ultrashort cavity with an ultranarrow bandwidth of PM-FBG and the linewidth of the laser is measured to be less than 2 kHz. The frequency linear tuning scheme has been theoretically and experimentally verified with a tuning range of more than 1 GHz, and the tuning resolution is near 3.1 MHz/nm. The repeatability and repeat accuracy during periodic tuning process also have been studied, showing that the laser has very stable linear frequency tuning.

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