

A wavelength-switchable single-longitudinal-mode dual-wavelength erbium-doped fiber laser for switchable microwave generation

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Abstract: A novel wavelength-switchable single-longitudinal-mode (SLM) dual-wavelength erbium-doped fiber laser (EDFL) implemented based on a sigma architecture that is composed of a ring loop and a linear standing wave arm is experimentally demonstrated. Gain competition that prevents stable dual-wavelength oscillation is effectively suppressed by placing the gain medium in the standing-wave arm and by introducing polarization hole burning (PHB) via polarization multiplexing of the two lasing wavelengths in the ring loop. The SLM operation is guaranteed by an ultranarrow Fabry-Perot filter (FPF) introduced by absorption saturation in an unpumped erbium-doped fiber (EDF) and the gain saturation in the gain medium. In addition, the ring cavity forms a Lyot filter for each wavelength. Thus, wavelength switching is achieved by simply adjusting the polarization state of either wavelength. By beating the two SLM wavelengths at a photodetector (PD), a microwave signal with a frequency tunable from ~10 to ~50 GHz is experimentally generated.

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1. Introduction

Multiwavelength single-longitudinal-mode (SLM) fiber lasers can find many applications in wavelength-division-multiplexing (WDM) communications, fiber optic sensors, modern instrumentation, and microwave photonics systems. Particularly, a wavelength-tunable or switchable dual-wavelength SLM fiber laser is a good candidate for frequency-tunable, high-power, and low-phase-noise microwave or millimeter-wave generation thanks to the advantageous features including broad wavelength tuning range, high output power, and narrow linewidth [1-8]. Compared with other microwave generation approaches such as optical injection locking [9], optical phase-lock loop [10] and external modulation [11], microwave generation using a dual-wavelength SLM fiber laser does not require a high-quality frequency-tunable microwave reference source, which would reduce significantly the system complexity and cost. However, to ensure a stable operation of an SLM dual-wavelength erbium-doped fiber laser (EDFL), two issues must be carefully addressed. First, the strong homogeneous line broadening and cross-gain saturation in the erbium-doped fiber (EDF) would lead to unstable dual-wavelength oscillation. A straightforward solution is to cool the EDF in liquid nitrogen (77K) [1], but it is not suitable for practical applications. Other solutions to eliminate the homogeneous line broadening and cross-gain saturation include the use of a hybrid gain medium [2], and the use of polarization hole burning (PHB) effect [3]. When a hybrid gain medium is used, a careful balance of the gains provided by the two gain media must be ensured, which may increase the complexity. Second, since a fiber ring laser usually has a long cavity with closely spaced longitudinal modes, an ultranarrow bandpass filter (BPF) with two transmission peaks must be incorporated to eliminate multi-longitudinal-mode oscillation and mode hopping. The ultra-narrow BPF can be realized using a saturable-absorber- (SA) based Sagnac loop [1], a multi-ring loop with a BPF [2-4], a phase-shifted fiber Bragg grating (FBG) [5-7], or a FBG-based Fabry-Perot filter (FPF) [8]. The major limitation associated with the use of a phase-shifted FBG or a FBG-based FPF is that the lasing wavelengths are not tunable. To realize wavelength-tunable operation, we have recently demonstrated a dual-wavelength and wavelength-tunable fiber laser having a multi-ring loop incorporating a tunable BPF [2]. Since the dual wavelengths were switched at the same time, the wavelength spacing was maintained; therefore the approach is not suitable for tunable microwave generation. Recently, Qian *et al.* also proposed a tunable dual-wavelength fiber laser [3] with the two lasing wavelength selected by two tunable filters. The PHB effect was employed to stabilize the operation. Since the free spectral range (FSR) of the laser cavity is much less than the 3-dB bandwidth of the fiber filters, the laser oscillation is very sensitive to the environmental variations.

In this paper, we propose a novel wavelength-switchable SLM dual-wavelength EDFL for frequency-tunable microwave generation. The proposed EDFL has a ring structure incorporating a linear standing wave arm. In the proposed system, polarization multiplexing is used to suppress the gain competition in the gain medium via PHB effect. Meanwhile, an unpumped EDF serving as an SA is inserted to create an ultranarrow BPF for the SLM selection. A reflection structure is adopted to form a standing-wave pattern in the SA as well

as in the gain medium, which would greatly enhance the PHB effect. In addition, the laser cavity is designed to form a Lyot filter for each wavelength, which is used for wavelength tuning by simply adjusting the polarization state of each wavelength. An experiment is carried out. A microwave signal with a frequency that is tunable from ~10 to ~50 GHz with a tunable step of ~10 GHz is generated by beating the two wavelengths at a photodetector (PD).

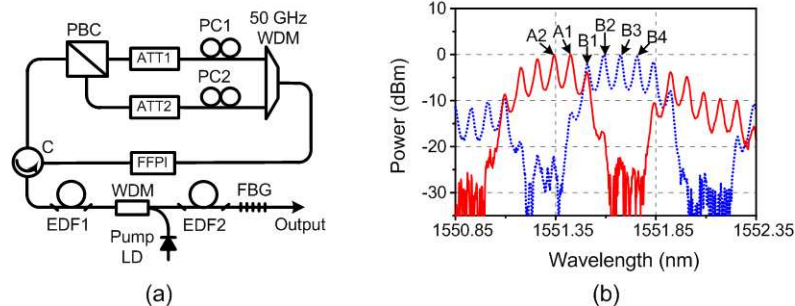


Fig. 1. (a) Configuration of the wavelength-switchable SLM dual-wavelength EDFL. EDF: erbium-doped fiber; LD: laser diode; WDM: wavelength-division multiplexer; PC: polarization controller; PBC: polarization beam combiner; C: circulator; FFPI: fiber Fabry-Perot interferometer, ATT: attenuator. (b) Open loop transmission spectra. Red solid line: Channel 1; Blue dotted line: Channel 2.

2. Principle

The schematic diagram of the proposed SLM dual-wavelength EDFL is shown in Fig. 1(a). It is built in a sigma configuration, in which a fiber ring loop is connected to a linear standing wave arm via a 3-port circulator. In the linear arm, a section of EDF (EDF1, Lucent HP980) with a length of 4 meters is used as gain medium. The EDF is pumped with a 980-nm laser diode (LD) through a 1550 nm/980 nm WDM coupler. To form a self-induced FBG with ultranarrow bandwidths, another section of unpumped EDF (EDF2) with a length of 2 meters is inserted in the arm which serves as an SA. A uniform FBG with a reflection peak at 1551.63 nm, a peak reflectivity of 94% and a 3-dB bandwidth of 0.74 nm is also incorporated in the arm, to reflect back the desirable wavelengths and to form a standing wave in the SA as well as in the gain medium. In the fiber ring loop, a fiber Fabry-Perot interferometer (FFPI, Micron Optics) with an FSR of 10.2 GHz and a finesse of 4 provides a coarse wavelength selection. To obtain dual-wavelength oscillation, the light wave from the output of the FFPI is split into two branches by a 50-GHz spacing WDM, with each branch having a polarization controller (PC) and a variable attenuator (ATT). The light waves from the two branches are then polarization multiplexed at a polarization beam combiner (PBC) to create two orthogonal polarization states for the two lasing wavelengths. The PBC is polarization-maintain-fiber (PMF) pigtailed at the two input ports. The total cavity loss for the two wavelengths without the SA is less than 8 dB. The laser output is monitored by an optical spectrum analyzer (OSA, Ando AQ 6317B) with a resolution of 0.01 nm, and the generated microwave signal is observed by an electrical spectrum analyzer (ESA, Agilent E4448A, 3 Hz-50 GHz).

To achieve stable dual-wavelength operation, we utilize the PHB effect to suppress the strong homogeneous line broadening and cross-gain saturation in the EDF. Generally, the PHB effect in an EDFL with a unidirectional cavity is very weak and therefore special techniques must be employed to enhance the effect [12]. In this work, the PHB effect is increased by letting the oscillation light waves propagate bidirectionally in the gain medium. A standing wave is thus formed, which would greatly enhance the PHB effect via spatial hole burning in the EDF.

In the setup, a 2-m long unpumped EDF is used as an SA. Because the absorption coefficient of an EDF is inversely proportional to the intensity of the optical light, when a standing wave is formed, the spatial optical power would distribute periodically along the EDF. Therefore, an absorption coefficient with periodic variation along the SA would be

created, which would result in a periodic refractive index change based on the well-known Kramers-Kronig relation, a weak FBG is thus generated. In this approach, we use a low doped EDF (doping concentration $\rho < 10^{19} \text{ Er}^{3+}/\text{cm}^3$) and a low injection power (the average power in the unpumped EDF is less than 10 mW). Assume that the overlap factor is around 0.5, the average refractive index change Δn is calculated to be less than 1.5×10^{-7} [13]. Taking into account the wavelength $\lambda \approx 1551 \text{ nm}$, the length of the unpumped EDF $L_g \approx 2 \text{ m}$, and the effective refraction index of the EDF $n_{\text{eff}} \approx 1.48$, the 3-dB bandwidth of the SA-induced FBG is calculated to be less than 6.7 MHz based on the formula given in [14]. In addition, the gain of an EDF amplifier is also inversely proportional to the intensity of the optical light. Therefore, the standing wave in the gain medium would form another self-induced FBG. The two FBGs would then form a self-tracking FPF. As a result, an ultranarrow BPF with a 3-dB bandwidth of less than 6.7 MHz is created. In the experiment, the total cavity lengths for the two wavelengths are about 30.4 and 31.8 m, corresponding to two FSRs of 6.7 and 6.4 MHz. The 3-dB bandwidth of the ultranarrow BPF is comparable to the FSRs of the cavities, indicating that the SLM condition is well satisfied. On the other hand, when a dual-wavelength lightwave signals propagate in the SA, the standing waves generated by the different wavelengths can exist independently in the SA with negligible interaction when the wavelength spacing is much greater than the cutoff frequency ($< 1 \text{ GHz}$) [1]. With polarization multiplexing of the two wavelengths, the interaction would be further reduced. As a result, simultaneous SLM lasing at two wavelengths is guaranteed.

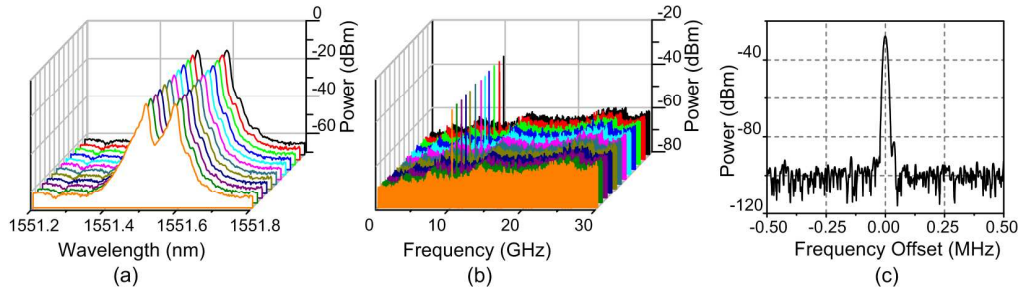


Fig. 2. Generation of 10-GHz microwave signal using the proposed fiber laser. (a) The optical spectra measured at a 3-min interval over a 36-min period; (b) the electrical spectra measured at a 3-min interval over a 36-min period, with RBW = 300 kHz; (c) the zoom-in view of the beating signal at SPAN = 1 MHz, RBW = 9.1 kHz.

The PBC used in the configuration is PMF pigtailed at the two input ports. The length of the PMF is about 0.5 meter, corresponding to a differential group delay (DGD) of 0.7 ps at 1550 nm. The PMFs and the PBC form two Lyot filters for the two channels if the input light waves are aligned with an angle of 45° with respect to the fast axes of the PMFs. Using the Jones matrix method, the transmission T of the Lyot filters can be expressed as [15]

$$T = \cos^2 \left(\frac{2\pi c}{\lambda} \cdot \Delta\tau + \theta \right), \quad (1)$$

where λ is the wavelength of the input light wave, $\Delta\tau$ is the DGD of the PMF, c is the light speed in vacuum, and θ is the relative phase difference of the two orthogonal polarization modes. From Eq. (1), the center wavelength of the Lyot filters can be tuned by changing θ , which can be implemented by adjusting the PCs. Fig. 1(b) shows the open loop transmission spectra of the two wavelength channels when the fiber loop is disconnected between the PBC and the circulator. The multi-transmission peaks are introduced by the uniform FBG, the FFPI and the 50-GHz WDM, with two adjacent peaks separated by $\sim 10 \text{ GHz}$, which are marked as A1, A2 in Channel 1 and B1, B2, B3, B4 in Channel 2. By adjusting PC1 and PC2, the Lyot filters would select one wavelength from A1 and A2, and another wavelength from B1, B2,

B3 and B4. As a result, the wavelength spacing between the two lasing wavelengths can be tunable from ~10 GHz to ~50 GHz with a step of ~10 GHz.

It should be noted that for most reported EDFLs, the gain medium is not placed in the standing wave arm or the bidirectional cavity because of the following two problems: 1) the spatial hole burning would stimulate some other undesirable modes, leading to serious mode hopping; 2) the self-induced FBG by the standing wave would reduce the amplification efficiency at the desired wavelengths. In our approach, the undesirable modes are removed by the self-induced ultranarrow BPF. Meanwhile, the self-tracking FPF introduced by the absorption saturation in the unpumped EDF and the gain saturation in the gain medium provides additional gains for the lasing wavelengths [16]. Thus the two problems do not present in the proposed system.

3. Experimental results and discussion

An experiment based on the setup shown in Fig. 1(a) is performed. To generate a microwave signal, the generated two wavelengths are sent to a PD. Fig. 2(a) shows the optical spectra of the laser output. Two wavelengths at 1551.51 and 1551.59 nm with a wavelength spacing of 0.08 nm corresponding to a difference frequency of 10-GHz are observed. In the experiment, the two wavelengths are selected by adjusting PC1 and PC2 to let one wavelength at A1, and the other at B1. The side-mode suppression ratios (SMSRs) are 46.9 and 45.7 dB. The two wavelengths are heterodyned at the PD. As shown in Fig. 2(b), only one beat note at 10.25 GHz is observed in the electrical spectrum, which demonstrates that the dual-wavelength laser is operating at SLM. Fig. 2(c) shows a zoom-in view of the beat signal, displayed on the ESA with a span of 1 MHz and a resolution bandwidth of 9.1 kHz. From Fig. 2(c), we can estimate that the 3-dB bandwidth of the obtained electrical signal is less than 10 kHz. We allow the system to operate in a room environment for a period of 36-min. The optical and electrical spectra are recorded at a 3-min interval, as shown in Fig. 2(a) and (b). No significant fluctuations are observed in the optical spectra. The wavelengths shift is less than 12 pm and the optical power fluctuation is smaller than 0.2 dB, which are within the measurement accuracy of the OSA. In the electrical spectra, the center frequency shifts are less than 100 MHz and the electrical power fluctuations are less than 1 dB. The frequency drift is mainly originated from the FFPI, which is very sensitive to the temperature variations. If the FFPI is controlled by a thermo-electric cooler (TEC), the frequency drift would be greatly reduced. It should be noted that B1 is located at the edge of Channel 1 and Channel 2, which means the optical light at B1 propagates in both branches. Therefore, the polarization direction of B1 is slight departure from the vertical direction of A1, which would partly decrease the PHB effects. However, stable operation is still obtained in the experiment, indicating that the homogeneous line broadening and cross-gain saturation in the EDF is greatly suppressed by the proposed method.

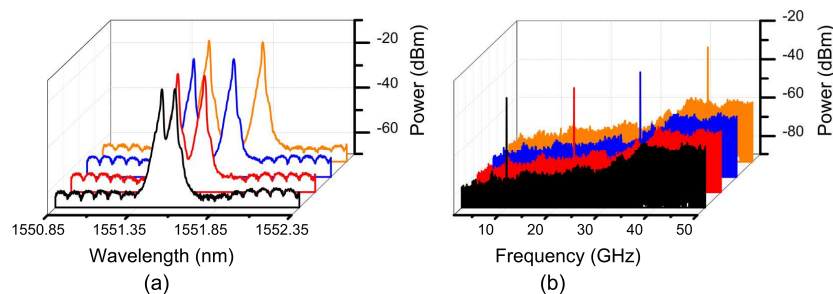


Fig. 3. The spectra of (a) the optical signal and (b) the generated electrical signal, with a frequency tuned from 10 to 40 GHz, RBW = 300 kHz.

The wavelength-switchability of the proposed fiber laser is also investigated. First, we tune PC1 to let one wavelength at A1 and adjust PC2 to let the other wavelength be switched from B1 to B4. As shown in Fig. 3(a), the wavelength in Channel 2 is switched from 1551.59,

1551.67, 1551.75 to 1551.83 nm, with a microwave beat note at 10.25, 20.48, 30.67 and 41 GHz observed on the ESA, respectively, as shown in Fig. 3(b). Then we tune PC2 to let one wavelength at B4, and adjust PC1 to let the other wavelength at A2. As shown in Fig 4(a), two wavelengths with a wavelength spacing of 0.41 nm are obtained and a beat note at ~51 GHz would be generated. To observe the 51-GHz signal using a low-frequency ESA, an external mixer (Agilent 11970U, 40-60 GHz) is used to down-convert the 51-GHz signal to a lower frequency. From Fig. 4(b) we can see, the center frequency of the beating signal is 51.34 GHz. The zoom-in view of the beat signal is shown in Fig. 4(c). Again, the 3-dB bandwidth is less than 10 kHz.

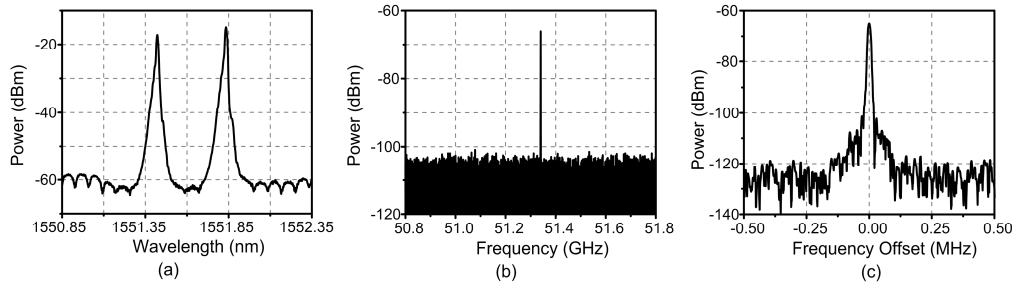


Fig. 4. Generation of a 50-GHz signal using the proposed fiber laser. (a) The optical spectrum; (b) the electrical spectrum at SPAN = 1 GHz, RBW = 300 kHz; (c) the zoom-in view of the 50-GHz signal at SPAN = 1 MHz, RBW = 9.1 kHz.

Due to the limited bandwidth of the PD, we only demonstrate the generation of a millimeter-wave at ~50 GHz. So far, a PD based on a uni-travelling carrier structure allows an effective detection of two phase-correlated wavelengths with a wavelength spacing corresponding to 914 GHz [17]. If we replace the uniform FBG by one with a wider bandwidth, and replace the 50-GHz WDM by a 500-GHz WDM, the SLM dual-wavelength EDFL should be able to generate two SLM wavelengths separated in the terahertz range. This implies that the proposed SLM dual-wavelength may be used to generate frequency-tunable terahertz waves. On the other hand, the tuning step is only determined by the FSR of the FFPI. If a FFPI with a smaller FSR is applied, the tuning step could be greatly reduced. Note that mode hopping within 100-MHz range is observed if large mechanical and acoustic vibrations are present. The mode hopping caused by the vibrations may be reduced if a large-finesse FFPI is used in the system, which would provide a better confinement of the lasing wavelengths.

3. Conclusion

A novel EDFL with stable dual-wavelength SLM oscillation to generate a frequency-tunable microwave signal was proposed and experimentally demonstrated. The proposed fiber laser was built in a sigma configuration composed of a ring loop and a linear standing wave arm. By placing the gain medium in the standing wave arm and by introducing PHB via polarization multiplexing of the two lasing wavelengths in the ring loop, the gain competition was effectively suppressed. The SLM operation was ensured by a self-induced ultranarrow FPF formed in the unpumped EDF and the gain medium. Wavelength tuning was achieved by changing the polarization state of either wavelength, to adjust the center frequencies of the two in-cavity Lyot filters. Two wavelengths both operating in SLM mode were generated. By applying the two wavelengths at a PD, a microwave signal with a tunable frequency from ~10 to ~50 GHz was experimentally obtained. The proposed system may find applications in radio-over-fiber systems, wireless sensor networks, instrumentation, and terahertz imaging systems.

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