Dual-wavelength fiber grating laser in linear overlapping cavity

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We report a switchable dual-wavelength fiber grating laser in linear overlapping cavity. The laser features two overlapping cavities sharing a single Yb-doped gain medium fiber and two sets of fiber Bragg gratings. A coiling fiber setup is inserted into the 1035 nm laser cavity. Given that the bending loss is inversely related to the bending radius, the cavity loss of 1035-nm can be modulated. Modulating the bending loss facilitates the switching of the fiber grating laser to a single-or dual-wavelength output at 1030 or 1035 nm and convenient tuning of the power ratio of the two wavelengths. An approximately 152.6-mW output power and up to 38-dB polarization extinction ratio are observed. The simultaneous lasing at 1030 and 1035 nm is a qualified seeder source for amplification to high power scale and can be applied to difference frequency generation of a terahertz signal. This dual-wavelength fiber grating laser is a potential pump source for generating terahertz radiation using a novel approach.

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The dual-wavelength laser has recently emerged as an international hot topic because of its extensive applications in differential absorption lidar, fine laser spectrum, laser medicine, and nonlinear frequency microwave conversion[1,2]. In particular, the use of dual-wavelength laser in difference frequency generation (DFG) of terahertz (THz) signal has attracted increasing interest because of its importance in homeland security, nondestructive testing, space exploration, and scientific experimentation involving sensing, imaging, and spectroscopy[3,4].

Nonlinear optical frequency conversion pumped by dual-wavelength fiber lasers is advantageous over other methods that produce THz signals given its narrow spectral width, remarkable stability, and simple optical structure[5,6]. Pump sources of THz systems utilizing a linear cavity that share a single piece of gain medium exhibit excellent timing and spatial synchronization characteristics[5,7,8].

However, Yb-doped fiber lasers suffer from compound-cavity mode competition because of their ordinary linear homogeneous broadening. Several methods, such as frequency-shifted feedback, four-wave mixing, and polarization hole burning (PHB), are employed to overcome this challenge[9,10]. In Ref. [10], a multi-wavelength erbium-doped fiber (EDF) laser configuration based on the PHB and overlapping cavity principle is proposed. Although polarization maintaining (PM)-fiber Bragg gratings (FBGs) are used in this report, the polarization states of multiple wavelength output are out of control and therefore cannot be used in DFG. Stability in Ref. [10] is also difficult to ensure. Any external disturbance such as vibration may result in altered polarization in the single-mode fiber (SMF). Polarization controllers should be readjusted to achieve multi–wavelength mode. In Ref. [11], a stable dual-wavelength PM EDF laser is demonstrated using an all PM linear cavity that utilizes two reflection peaks from the PM-FBG. However, the maximum range of separation of the dual wavelengths is only~0.22 nm, restricted by the birefringence of the PM-fiber. Thus, the DFG frequency is limited and cannot generate THz signal. Additionally, the dual laser lines simulated along two orthogonally linearly polarized modes and the power ratio of the two wavelengths are not adjustable and cannot satisfy the application in DFG, which requires two laser lines with certain power ratio.

In this study, an innovative laser, with linearly polarized dual-wavelength emission and tunable power ratio, is proposed by employing a tunable bending loss into the loss of cavity. We demonstrate the operation of a linear cavity dual-wavelength fiber laser using two sets of PM-FBGs that defines two laser emission lines at 1030 and 1035 nm. A setup of coiling fiber is programmed to coil the single mode fiber in the cavity of the 1035 nm laser to achieve power-ratio tuning, which ensures the efficient use of energy in DFG. Moreover, the setup of coiling fiber illustrates an innovative path to realize two simulating wavelengths with larger separation, rather than only with near separation in as shown in Refs. [10,11]. The employment of the linear cavity guarantees the natural timing and spatial synchronization of the dual-wavelength laser beam, which is the key factor in improving the conversion efficiency of the DFG of the

THz signal. Furthermore, it is eligible as the master oscillator to seed a fiber master oscillator power amplifier (MOPA) system that has favorable power scaling potential. This power-ratio tunable dual-wavelength laser that provides simultaneous lasing at 1030 and 1035 nm in a linear cavity is innovative and not expensive. It also prognosticates a potential simpler method for generating THz radiation.

The experimental setup of the proposed fiber laser is shown in Fig. 1. The linear cavity consisted of two sets of FBGs, and a 2.5-m Yb-doped single cladding fiber served the gain medium. Two wavelengths, λ_1=1035 nm and λ_2=1030 nm, were reflected by FBG1 and FBG2, respectively. The gain fiber was pumped by a SMF-coupled diode laser emitting 400 m W at 976 nm through a filter wavelength division multiplexer (WDM) spliced at one end of the cavity. A dichroic mirror, with high transmittance at 1030 nm and high reflectivity (HR) at 975 nm, was placed inside the WDM. The gain fiber used was a PM single-mode Yb-doped silica fiber (PM-YSF-HI) with a core diameter of 6 μm (numerical aperture 0.11), a birefringence of 2.5 $\times$ 10^{-4}, and a peak absorption coefficient of 250 dB/m at 976 nm in the small-signal regime. The absorption and emission spectra of the material in the active fiber is shown in Fig. 2. The output end of the fiber was cut by 8° to eliminate back reflection. In this system, all fibers and fiber-based components in the cavity were PM.

The reflectivity and transmission of the FBGs are shown in Fig. 3. The FBG1 set has HR of 99% and low reflectivity (LR) of 9.5%. The FBG2 set has a HR of 99% and a LR of 8.5%. The FBGs were fabricated by focusing a collimated KrF excimer laser beam (PM844, Lumonics) through a phase mask onto a horizontally positioned fiber in Ryerson University in Canada. We spliced all the PM fibers by Fujikura Fusion Splicer (FSM-45PM-LDF) and automatically aligned the axis. Only the LR-FBG was spliced to the end of the gain fiber after a 90° rotation (Fig. 1). With the FBG polarization selection technique[12], the slow axis wavelength of the LR-FBGs matches with the fast axis wavelength of the HR-FBGs, whereas the fast axis wavelength of the LR-FBGs and slow axis wavelength of HR-FBGs do not overlap each other. Thus, dual wavelength can oscillate only one polarization along it. However, achieving dual-wavelength lasing at room temperature is difficult. Only one simulating wavelength 1035 nm laser can be utilized because the cavity loss of 1035- nm is lower than that of 1030 nm. To overcome this major limitation, a coiling fiber setup was inserted into the 1035-nm laser cavity to modulate the cavity loss in the 1035-nm laser. In our experiment, the HR gratings of the two wavelengths were imprinted together on a PM silica fiber. HR-FBG1 on the silica fiber was a few millimeters away from HR-FBG2, leaving space for the fiber to be coiled by the setup shown in Fig. 4. The diameter of the mandrel was 6 mm with many spiral grooves on it. The fiber increased along the grooves and was a little loose to avoid being scratched. In our experiment, approximately 1.5 loops of fiber were coiled to achieve a dual-wavelength lasing. The coil length and diameter of the coiled fiber were tuned by rotating the orange arm. The cavity loss of the laser resonator λ_1 is modulated, but the cavity loss of the laser resonator λ_2 remain essentially constant.

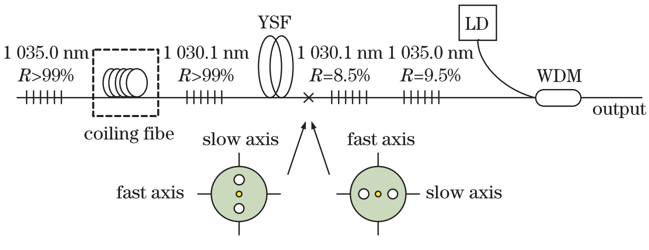

Fig. 1. Experimental setup of the switchable dual-wavelength fiber laser.

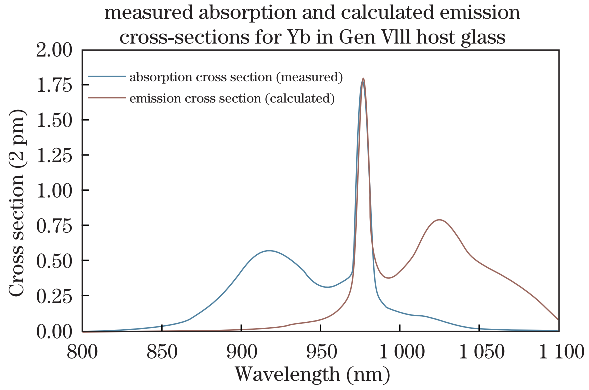

Fig. 2. Absorption and emission spectra of the material in active

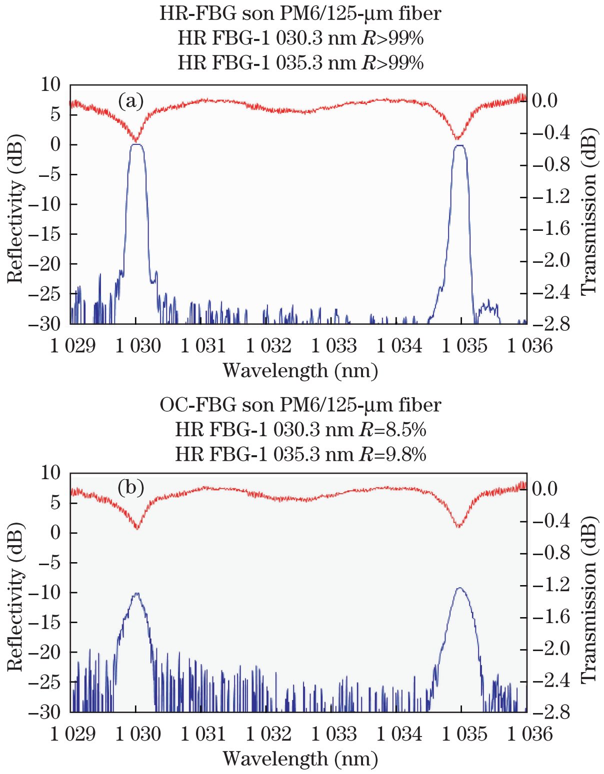

Fig. 3. Reflectivity and transmission of the FBGs.

The FBG laser without a coiled fiber exhibits a single-wavelength output at 1035-nm (Fig. 5). The output can achieve a power of 253.0-m W and a slope efficiency of 70.8%. The high reflective of the LR-FBG1 and the Yb^{3+} low absorption at the 1035 nm wavelength has resulted in only the 1035-nm laser operating in a single Yb-doped

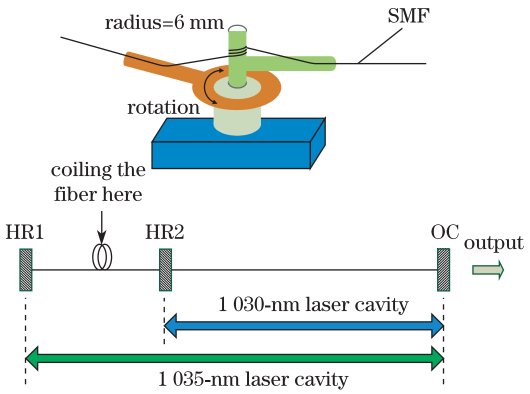

Fig. 4. Coiling fiber setup applied to single-mode fiber between HR-FBG1 and HR-FBG2.

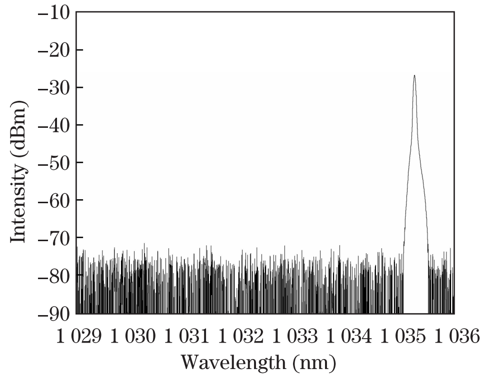

Fig. 5. Single wavelength output of the FBG laser without a coiling fiber setup.

fiber at room temperature.

To obtain stable dual-wavelength lasing at room temperature, the following equation should be satisfied:

$$g_{\lambda_i} \times L = G_{\text{th}}(\lambda_i) = \delta_{\lambda_i}, i = 1, 2, \qquad (1)$$

where g_{λ_i} is the gain coefficient of λ_i, L is the length of the Yb-doped fiber, $G_{\text{th}}(\lambda_i)$ is the threshold of single-pass gain of λ_i, and δ_{λ_i} is the single-pass loss of λ_i.

The single-pass loss δ_{λ_i} can be controlled to achieve wavelength switching. Given that the bending loss is inversely related to the bending radius, a coiling fiber setup was programmed (Fig. 4) to obtain dual-wavelength operation with a single piece of Yb-doped fiber. In Ref. [13], the macro-bend loss in low-loss optical waveguide was studied theoretically. The following equation for bending loss in standard SMFs was derived from[13]

$$A = \frac{\pi}{2R}\frac{10^4}{\sqrt{\Delta}}10^{1.29-2.17\xi R_n-0.58\xi^2 R_n^2}(\text{dB/cm}), \qquad (2)$$

where $\xi = \Delta^{3/2}1.137^{\Delta-0.01}$, $R_n = n_2R/\lambda_0$, and $\Delta = (n_1 - n_2)/n_2$, R is the bending radius of the optical fiber, λ_0 is the central operating wavelength, and n_1 and n_2 are the refractive indices of the fiber core and cladding, respectively. $n_1 = 1.454$ and $n_2 = 1.450$ at λ_0=1.03 μm, and Δ is the relative difference in refractive indices of the optical fibers. λ_0 and R are expressed in micrometers[13]. The bending loss that is inversely related to the bending radius is shown in Fig. 6.

Introducing loss by the coiling fiber setup facilitates the modulation of the loss of the resonator of laser I δ_{λ_1}, whereas the loss of the resonator of laser II δ_{λ_2} is constant. With the proper adjustment of the coiling fiber setup, the laser was operated in either single (1030 or 1035 nm) or dual wavelength mode, and the power ratio of the two wavelengths was adjusted.

Typical spectra of the laser are shown in Fig. 7. The YOKOGAWA AQ6370B optical spectrum analyzer in 0.02-nm resolution shows that the 3-dB bandwidth of 1030 and 1035 nm are 0.036 and 0.038 nm, respectively.

A dual-wavelength output, which can be used as a compact, easily-integrated THz pump source, has been achieved from a single optical fiber. To apply this fiber laser in the DFG of THz signal, the bending radius and bending length were modulated to achieve stable dual-wavelength output with equal amplitudes. The proposed method is advantageous over other techniques because of its simple design, good repeatability, and precise control of stable dual-wavelength lasing. Considered a dual-wavelength equal-amplitude laser, the spectrum and experimental beam profile in the far field are shown in Fig. 8. The 3-dB bandwidth of the dual-wavelength laser is 5.0009 nm, and M^2 of the output beam is 1.05, which was measured by a laser quality monitor-HP according to

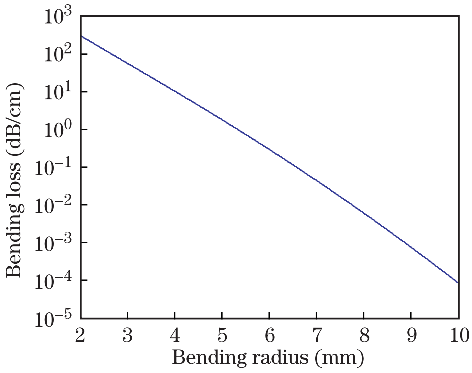

Fig. 6. Relationship between the radius and bending loss in single-mode fiber.

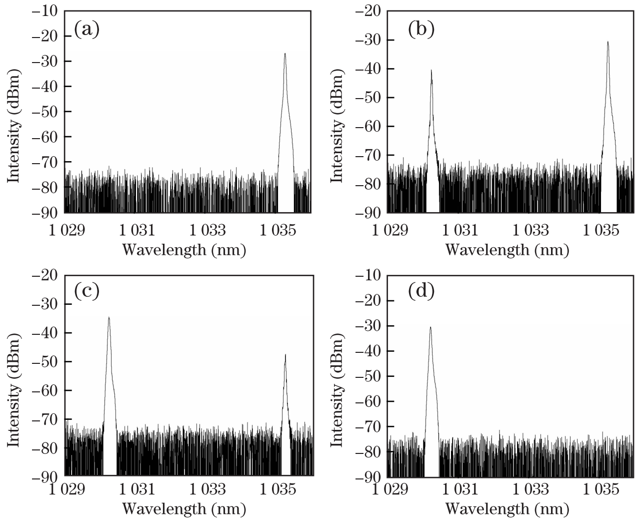

Fig. 7. Output spectra of the proposed laser with various power ratios.

second-order-moment-based width definition. The output power reaches 223.5 mW, with a slope efficiency of 65.3%. The stability was examined within 60 min. The spectra are unchanged in either dual-or single-wavelength operation. Power variation of less than 5.0% is found.

The polarization extinction ratio (PER) of the laser output with 8° cut is 20 dB, which is measured with a high-quality Glan polarizer. To obtain high PER, an isolator was added in the output. The isolator with an insertion loss of 1.6 dB and PER of 38 dB was made by AFR Corporation. Although the output power is sacrificed to 152.6 mW, a dual-wavelength laser output, an eligible seeder source for PM Yb-doped MOPA system with an excellent PER of 38 dB, is proposed.

THz has attracted much attention because of its ability to penetrate common materials without damaging the human tissue[14]. Using the 1030 and 1035 nm dual-wavelength lasers, we selected collinear matching DFG in GaP crystal to generate THz radiation in the following experiment. The collinear matching method does not require the rotation of the crystal or alteration of the pumping incident angle of light[15]. The dual-wavelength laser emitting from one gain medium can increase the space range of three-wave interaction without complex alignment technology, remarkably reducing the difficulty in operation. The GaP crystal is an ideal crystal for nonlinear DFG of THz radiation because of its larger two-order nonlinear coefficient, low absorption coefficient, and strong phase matching ability[16]. The collinear phase matching curves corresponding to different temperatures of the GaP crystal are shown in Fig. 9.

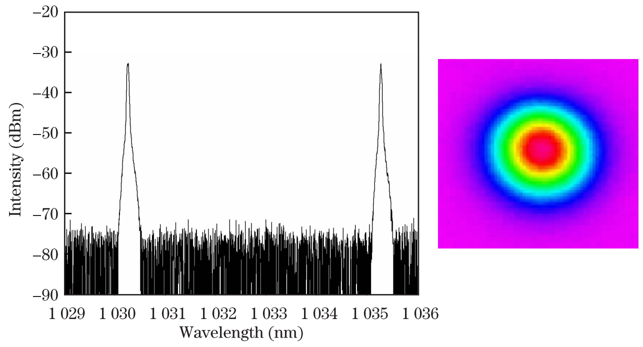

Fig. 8. Output spectrum of the laser while tuned to equal-amplitude dual-wavelength output and experimental output beam profile in the far field.

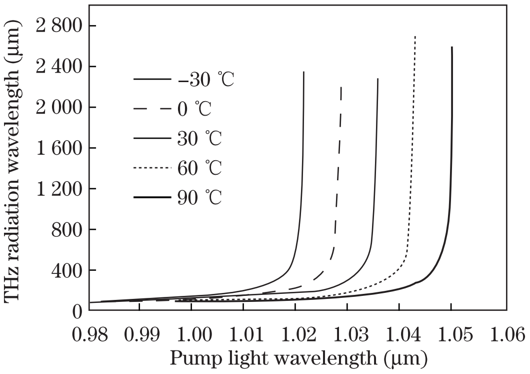

Fig. 9. Collinear phase matching curves corresponding to different temperatures of the GaP crystal.

Compared with other near-infrared lasers, the pump light laser of wavelength at 1.03 μm is advantageous because not only does it fall in the matching wavelength range at near room temperature, but it is also in the small peak of the Yb emission cross section. With temporal and spatial coherence, as well as excellent beam quality, the 1030 and 1035 nm dual-wavelength laser is considered amplifiable to high-power scale by a PM MOPA system[17] to achieve a THz radiation of approximately 1.407 THz. Further studies will involve the continuous stretching or thermal application of the wavelength of FBGs. Broadband tuning of THz radiation will be accomplished.

In conclusion, we propose a dual-wavelength fiber grating laser that can be used for THz generation by difference frequency. The dual-wavelength laser was assembled using a single piece of gain fiber, two sets of fiber gratings, and a coiling fiber setup. Given that the bending loss is inversely related to the bending radius, the output can be switched to single- or dual-wavelength mode using the coiling fiber setup, and the power ratio of the two wavelengths can be tuned conveniently. Further studies on the enhancement of the power scale and tuning of the separation of two wavelengths are recommended to obtain highly efficient difference frequency and a tunable THz signal.

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