Ultranarrow dual-transmission-band fiber Bragg grating filter and its application in a dual-wavelength single-longitudinal-mode fiber ring laser

Xiangfei Chen

Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada, and Broadband Optical Network Research Laboratories, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

Jianping Yao and Zhichao Deng

Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada

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A fiber Bragg grating filter with ultranarrow dual-transmission bands implemented using the equivalent phase shift technique is demonstrated. A fiber ring laser that incorporates a dual-transmission-band fiber Bragg grating filter in the ring cavity is implemented. Dual-wavelength single-longitudinal-mode lasing with a wavelength spacing as small as 0.147 nm at room temperature is experimentally demonstrated.

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Phase-shifted fiber Bragg gratings (FBGs) are attractive for applications such as optical narrowband filters,[1] fiber lasers,[2] broadband optical signal processors[3] and optical CDMA.[4] Phase-shifted FBGs can be fabricated by introducing a true phase shift using a piezoelectric transducer or a phase-shifted phase mask. However, the use of a phase-shifted phase mask is inflexible with high cost. Postprocessing of a FBG can also introduce phase shift, but it is difficult to implement in a one-step fabrication with an accurate phase shift, especially for FBGs with complex phase-shift profiles. Recently, a technique to introduce an equivalent phase shift (EPS) into a FBG was proposed.[5] In the fabrication of an EPS FBG, the fiber and the phase mask are both fixed. In addition, the EPS can be controlled more precisely because it requires only micrometer precision instead of nanometer precision. Thus there are fewer phase fluctuations than with the true phase-shift method, in which the fiber or the phase mask must be shiftable. EPS FBGs have been successfully employed in different fiber-optic systems such as distributed feedback lasers,[6] optical CDMA coding,[5] and stable single-longitudinal-mode (SLM) fiber ring lasers.[7] Although multiwavelength fiber ring lasers have been reported recently, very few of them are operating in SLM with good stability. For a stable multiwavelength SLM fiber ring laser, two issues must be carefully addressed. First, to achieve SLM operation, an optical filter with ultranarrow bandwidth must be used to restrict the number of modes to one.[7] Second, instead of using erbium-doped fiber (EDF) with strong competition among different wavelengths,[8] nonhomogeneous-line-broadening gain materials, such as semiconductor optical amplifiers (SOAs), should be used to generate stable multiwavelength lasing at room temperature.[9] In this Letter, a fiber ring laser incorporating a dual-transmission-band EFS FBG filter with a SOA as the gain medium is implemented to generate dual-wavelength SLM lasing. Dual-wavelength SLM operation at room temperature with a wavelength spacing as small as 0.147 nm is demonstrated. To the best of our knowledge, this is the first stable room-temperature SLM dual-wavelength fiber laser with a simple ring structure and small wavelength spacing, implemented by employing an ultranarrow dual-transmission-band FBG filter.

A sampled fiber Bragg grating (SFBG) has multiple reflection peaks (channels), for it is made by periodically changing the refractive index modulation of a uniform or chirped FBG. In a regular SFBG, the sampling period is constant. However, if one sampling period is changed, while the other sampling periods are kept constant, an EPS will be introduced[5] with an ultranarrow transmission band. Usually, the channel with $m=-1$ is preferred since it is easier to implement with higher transmission. An ultranarrow single-transmission-band FBG filter has been demonstrated by introducing an EPS.[7] To obtain dual-wavelength transmission bands, two EPSs are necessary. Figure 1 shows the schematic diagrams of the index modulation profile of a FBG with dual-transmission bands. The FBG has 24 samples with a

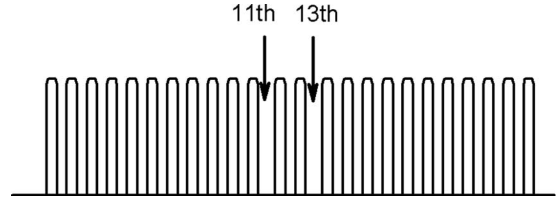

Fig. 1. Schematic diagram of the index modulation profile of a dual-transmission-band EPS FBG.

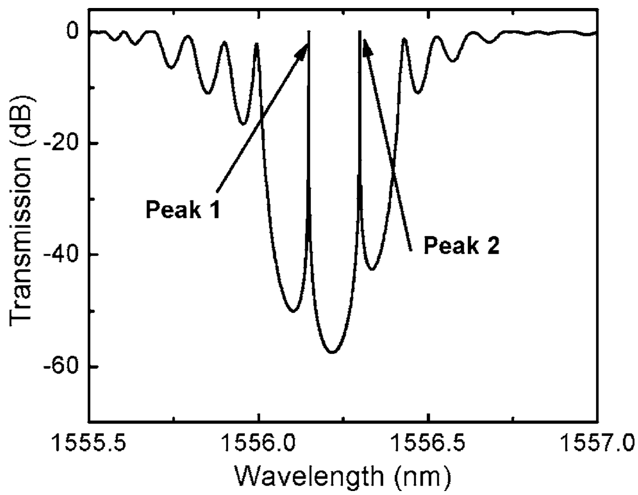

Fig. 2. Calculated optical spectrum of a FBG with two EPSs at the 11th and 13th samples.

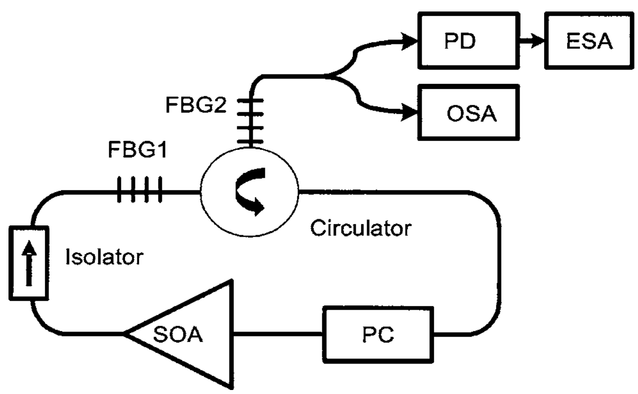

Fig. 3. Schematic diagram of the dual-wavelength fiber ring laser: PC, polarization controller; PD, photodetector, ESA, electrical spectrum analyzer; OSA, optical spectrum analyzer; SOA, semiconductor optical amplifier.

sampling period of 0.56 mm. To obtain two EPSs, the sampling periods of the 11th and 13th samples are changed to 0.84 mm. Thus two EPSs are introduced in the positions of the 11th and 13th samples.

The corresponding transmission spectrum in the vicinity of the $m=-1$ channel is shown in Fig. 2. In calculating the transmission spectrum, the maximum index modulation is 1.0×10^{-3} and the duty cycle is 0.5. From Fig. 2, it is seen that there are two transmission peaks in the $m=-1$ channel. The 3 dB bandwidths of the transmission bands are calculated to be 0.2 pm (peak 1) and 0.3 pm (peak 2).

A fiber ring laser that incorporates the dual-transmission-band EPS FBG filter is shown in Fig. 3. The fiber laser has a typical fiber ring structure, but the gain medium in the cavity is a SOA rather than an EDF to avoid strong homogeneous line broadening of EDFs. FBG1 is the dual-transmission-band EPS FBG. A second FBG, FBG2, is fabricated by superimposing two regular FBGs at the same location of the fiber with two reflection peaks, which is used to select the two transmission bands of FBG1. To minimize the cavity length, the output of the laser is obtained at the other end of FBG2.

The FBGs in our experiments are fabricated using a frequency-doubled argon-ion laser emitting at 244 nm. For the dual-transmission-band FBG (FBG1 in Fig. 3), the sampling is implemented by switching on and off the UV scanning beam using an electrically controlled optical shutter. The half-width at half-maximum of the UV beam along the direction of the fiber measured at the fiber is ~0.2 mm with a UV power of 60 mW. The fiber for FBG fabrication is a photosensitive cladding-mode suppression fiber that is hydrogen loaded for 10 days at 140 atm to further increase its photosensitivity. FBG1 is fabricated by one UV exposure. Because the UV laser beam has a super-Gaussian shape, in each sample there exists an area with no UV exposure, and the refractive index along the FBG is not constant. It is known that the higher the index modulation the larger the average refractive index. Since the maximum index modulation is high ($\geqslant 1.0\times10^{-3}$) in FBG1, to achieve a π EPS, one must ensure that the change of the sampling period is not exactly equal to half the sampling period. In such a situation, the change of the sampling periods is varied with the maximum index modulation and the effective duty cycle of the sample. For FBG1 in our experiment, the change of the sampling period is ~40%, or 0.224 mm. That is, in FBG1, the sampling periods related to the two EPSs are both 1.4×0.56 mm$=0.784$ mm.

The transmission spectrum of FBG1 is shown in Fig. 4, where the solid curve shows the measured spectrum and the dotted curve shows the calculated spectrum. The true insertion loss of the two transmission peaks cannot be measured because of the 0.01 nm resolution limit of the optical spectrum analyzer (Ando AQ 6317B). The simulated spectrum is obtained using a maximum modulation index of 1.0 $\times10^{-3}$ and the effective duty cycle is 0.46. The 3 dB linewidth of the peak is estimated to be 0.4 pm. The

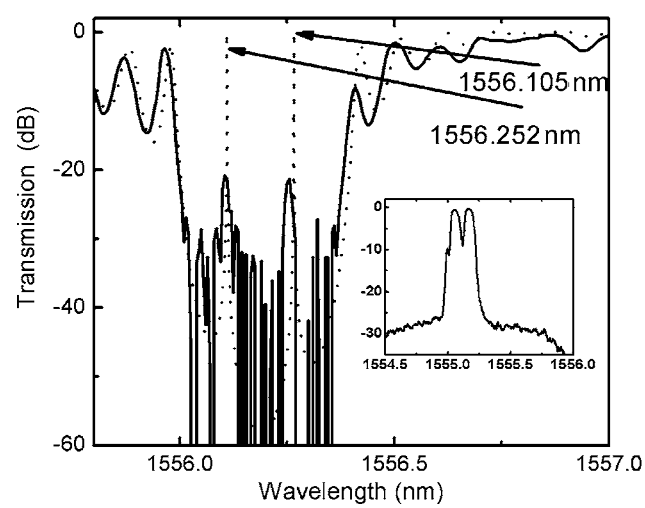

Fig. 4. Transmission spectrum of the dual-transmission-band FBG. Solid curve, measured spectrum; dotted curve, simulated spectrum. Inset, measured reflection spectrum of FBG2.

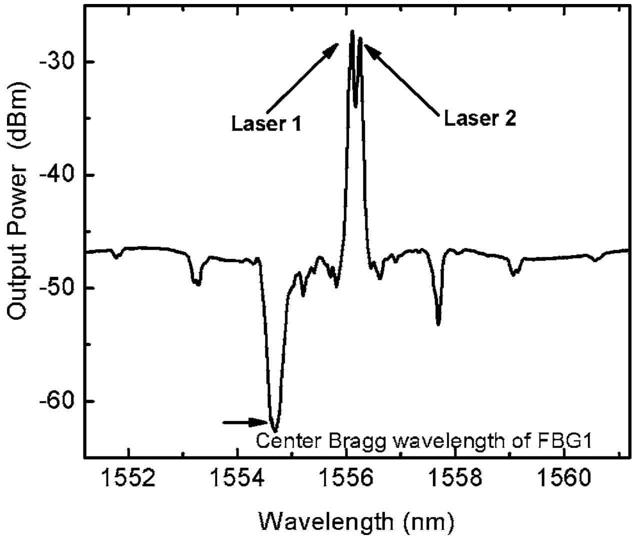

Fig. 5. Output optical spectrum of the dual-wavelength fiber ring laser.

wavelengths of the two transmission peaks are 1556.252 and 1556.105 nm with a wavelength spacing of ~0.147 nm. FBG2 is a reflection FBG with two reflection peaks to match the two transmission bands of FBG1. FBG2 is fabricated through inscription of two superimposed FBGs at the same location of the fiber. The measured reflection spectrum of FBG2 is shown in the inset of Fig. 4. To obtain a balanced effective gain for the two lasing wavelengths, the wavelength spacing between the two superimposed FBGs in FBG2 is 0.115 nm, slightly different from the wavelength spacing between the two transmission bands of 0.147 nm.

The two FBGs are incorporated in the configuration shown in Fig. 3. To achieve a balanced gain for the two lasing wavelengths, FBG2 is tuned by applying strain. When we carefully tune FBG2 and the polarization controller (PC), a stable dual-wavelength lasing is obtained. The lasing spectrum is shown in Fig. 5. As can be seen from Fig. 5, the two lasing wavelengths are 1556.104 and 1556.251 nm, which exactly match the two transmission bands shown in Fig. 4. The total output power is ~6 μW. Note that to achieve dual-wavelength SLM lasing, the pumping current cannot be higher than 160 mA, to give other longitudinal modes a net gain smaller than the threshold; SLM operation is thus guaranteed. In the experiment, the dual-wavelength SLM lasing is achieved at room temperature when the SOA injection current is 145 mA.

To verify that the dual-wavelength laser is operating in SLM, we apply the lasing output to a photodetector. No beating signals between the longitudinal modes are observed, which demonstrates that the two lasing wavelengths are truly in SLM. If the two peaks of FBG2 are tuned away from the $m=-1$ channel, the fiber ring laser will no longer operate in SLM, and beating signals between the longitudinal modes are then observed.

We should note that, in the fiber ring configuration, all components except the SOA are not polarization maintained. The polarization state may change when the environment conditions are changed, which leads to a change in the SOA gain. In the experiment, the PC has to be tuned to maintain a stable dual-wavelength lasing. It is believed that the system stability will be significantly improved if polarization-maintaining components are employed.

In summary, a dual-transmission-band FBG filter implemented using the EPS technique has been demonstrated. The FBG filter had two transmission bands with an estimated ultranarrow bandwidth of ~0.4 pm. As a direct application, a fiber ring laser incorporating the dual-transmission-band FBG filter was built. Dual-wavelength SLM operation at room temperature with small wavelength spacing was realized when a SOA was used in the laser cavity as a gain medium. The stability of the laser can be improved if polarization-maintaining components, such as polarization-maintaining fibers, polarization-maintaining circulators, are used. It should be noted that, to guarantee an absolute SLM operation, the linewidth of the two transmission bands must be small enough to ensure that only a SLM can survive while others are suppressed. However, the transmission bands are in fact resonant peaks and are sensitive to the intrinsic loss of the grating. It is known that hydrogen-loaded fiber has increased loss in the fiber. Compared with a single-transmission-band FBG written on non-hydrogen-loaded fiber,[7] the effective insertion loss of the transmission peaks in the present experiment is higher and the performance is decreased. It is expected that a better dual-wavelength SLM laser can be demonstrated with strong photosensitive fiber without hydrogen loading.

J. P. Yao's e-mail address is jpyao@site.uottawa.ca.

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