Optical Fiber Technology 17 (2011) 120–123

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Dual-wavelength single-longitudinal-mode erbium-doped fiber laser based on inverse-Gaussian apodized fiber Bragg grating and its application in microwave generation

Bo Lin [a], Swee Chuan Tjin [a,*], Han Zhang [a], Dingyuan Tang [a], Sheng Liang [b], Jianzhong Hao [c], Bo Dong [c]

[a] *Photonics Research Centre, School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore*
[b] *School of Instrument Science and Opto-electronics Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, China*
[c] *Institute for Infocomm Research, 1 Fusionopolis Way, Singapore 138632, Singapore*

ARTICLE INFO

Article history:
Received 19 October 2010
Revised 7 December 2010
Available online 4 February 2011

Keywords:
Fiber Bragg grating
Inverse-Gaussian apodization
Single-longitudinal-mode operation
Microwave

ABSTRACT

We propose a simple erbium-doped fiber ring laser. It consists of an inverse-Gaussian apodized fiber Bragg grating filter which has two ultra-narrow transmission bands, and an unpumped erbium-doped fiber as a saturable absorber. Stable dual-wavelength single-longitudinal-mode lasing with a wavelength separation of approximately 0.082 nm is achieved. A microwave signal at 10.502 GHz is demonstrated by beating the dual wavelengths at a photodetector.

© 2011 Elsevier Inc. All rights reserved.

1. Introduction

Dual-wavelength single-longitudinal-mode (SLM) fiber laser has attracted a lot of interests due to its ability to generate microwave signals, which have potential applications in software-defined radio, broadband wireless access network, optical sensing systems and so on [1–3]. Such a dual-wavelength fiber laser is utilized in microwave generation since it does not require a high-quality microwave reference source and hence reduces the system cost. So far, some works have been proposed to realize dual-wavelength SLM lasing based on fiber Bragg grating (FBG) filters [4–12], including phase-shift (PS) FBG [4,5], polarization-maintaining (PM) FBG [6,7], equivalent phase shift (EPS) FBG [8,9], and an FBG pair [10–12]. In this paper, we present a new method of generating a dual-wavelength SLM laser using an inverse-Gaussian apodized (IGA) FBG (IGAFBG) that has been explained in detail in our previous publications [13,14]. The system comprises an IGAFBG and a saturable absorber (SA) in an erbium-doped fiber ring laser configuration. It is found that this system produces stable dual-wavelength SLM lasing with a wavelength spacing of 0.082 nm. The microwave signal thus generated at 10.502 GHz beat frequency, by beating the two wavelengths at a photodetector, is also found to be extremely stable.

2. Dual-wavelength passband filter based on an IGAFBG

The principle behind the use of IGAFBG as an ultra-narrow dual-wavelength passband filter has been explained in [13,14]. A 20 mm long IGAFBG was fabricated using the phase-mask scanning technique using a 53 mW UV light from a 244 nm frequency-doubled argon laser focused through a cylindrical lens and a uniform phase mask with a pitch of 1065.7 nm, onto the core of a hydrogen loaded single-mode fiber. To realize the inverse-Gaussian apodization function $A(z) = 1 - \exp\left\{\left[-4(\ln 2)z^2\right]/(L/3)^2\right\}$ (assuming that the grating starts at $-L/2$ and stretches to $L/2$ in the z dimension), we chose a scanning speed profile of the translation stage to be $V(z) = 0.03 \times (A(z) + 0.1)^{-1}$ mm/s to best fit the $A(z)$ profile. Fig. 1 shows the measured (solid line) and the simulated (dashed line) transmission spectra of the IGAFBG. The two spectra are in a good agreement with each other. The simulated result is obtained using the transfer matrix method [15], with the effective refractive index taken as 1.447, the grating length L taken as 20 mm, the grating period taken as 532.85 nm, the index modulation depth taken as 1.6×10^{-4}, and the inverse apodization function $A(z)$ given above. Two transmission bands at 1542.995 and 1543.077 nm with ultra-narrow 3 dB bandwidths are observed in Fig. 1. Due to the limited 0.01 nm resolution of the optical spectrum analyzer (OSA) used in the experiment, the true 3 dB bandwidths of the two transmission bands cannot be accurately resolved. The wavelength spacing between the two channels is approximately 0.082 nm.

* Corresponding author.
E-mail address: esctjin@ntu.edu.sg (S.C. Tjin).

1068-5200/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.yofte.2011.01.002

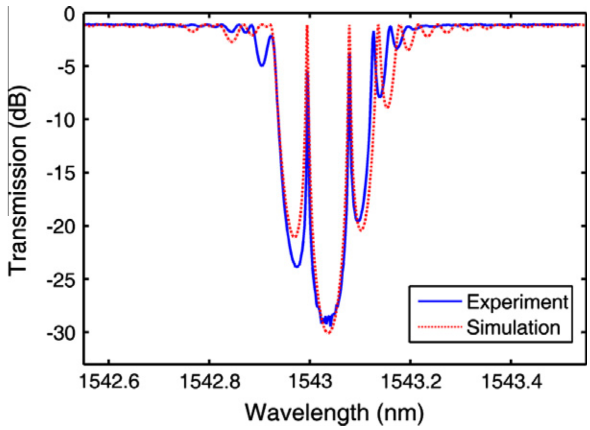

Fig. 1. Transmission spectra of the IGAFBG filter with a wavelength spacing of 0.082 nm (two peaks are at 1542.995 and 1543.077 nm). Solid line, measured spectrum. Dashed line, simulated spectrum.

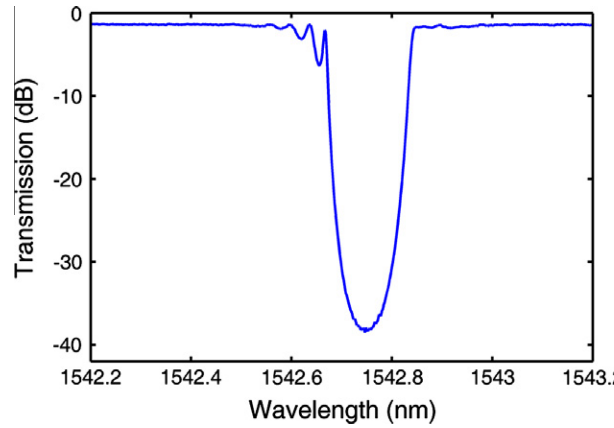

Fig. 3. Experimentally measured transmission spectrum of the uniform FBG.

3. Microwave generation from the proposed dual-wavelength SLM fiber ring laser

The schematic diagram of the proposed dual-wavelength SLM fiber ring laser is shown in Fig. 2. A 4 m long erbium-doped fiber (EDF), pumped with a 1480 nm laser diode through a 1480/1550 nm wavelength division multiplexer (WDM), serves as the gain medium. An IGAFBG of length 20 mm, and whose transmission spectrum is shown in Fig. 1, acts as a dual-wavelength passband filter with a wavelength spacing of 0.082 nm. A uniform FBG with a Bragg wavelength at 1542.75 nm, transmittivity of 35 dB, and a 3 dB bandwidth of around 0.16 nm, is tuned by applying a strain along the fiber axis, to select and reflect the two transmission bands of the IGAFBG. Fig. 3 shows the experimentally measured transmission spectrum of the uniform FBG. A 2 m long unpumped EDF with an absorption coefficient of 5.2 dB/m at 1530 nm serves as an SA (see Fig. 2) while the polarization controller (PC) is used to fine tune the cavity birefringence. Laser output was coupled out via the 10% port of the 90/10 optical coupler (OC), of which 10% of it was monitored by an OSA. The other 90% output power was channeled to the photodetector (PD) after the amplification by an erbium-doped fiber amplifier (EDFA). The microwave signal at the output of the photodetector was monitored using an electrical spectrum analyzer (ESA). By adjusting the PC carefully under a 230 mW pump power, we obtained a stable dual-wavelength lasing. Fig. 4a shows the repeated scans of the two lasing lines at a 6-min interval over an hour at room temperature. The laser emits simultaneously at 1542.996 and 1543.078 nm with a wavelength separation of 0.082 nm, which match the two transmission bands of the IGAFBG shown in Fig. 1. The optical signal-to-noise ratio (OSNR) for these two lasing lines is more than 30 dB. The laser output power fluctuation is shown in Fig. 4b, which shows that the maximum power fluctuation at the dual wavelengths is less than 1 dB, illustrating good stability in the output power of the fiber laser. The wavelength variation is beyond the resolution limit of the OSA, which is shown in Fig. 4c. A microwave signal was observed in the ESA and Fig. 5a shows the measured result in a 20 GHz span with a resolution of 1 MHz. Only one beat frequency was observed, which suggests that the dual-wavelength fiber laser is operating in SLM at the lasing wavelengths. Fig. 5b shows the result in a 2 MHz span with a resolution of 10 kHz. The central frequency of the microwave signal is approximately 10.502 GHz, corresponding to a wavelength separation of 0.082 nm of the two lasing lines. The central frequency shift is within 1 MHz, and shows good stability with time. The 3 dB bandwidth of the microwave signal is less than 10 kHz.

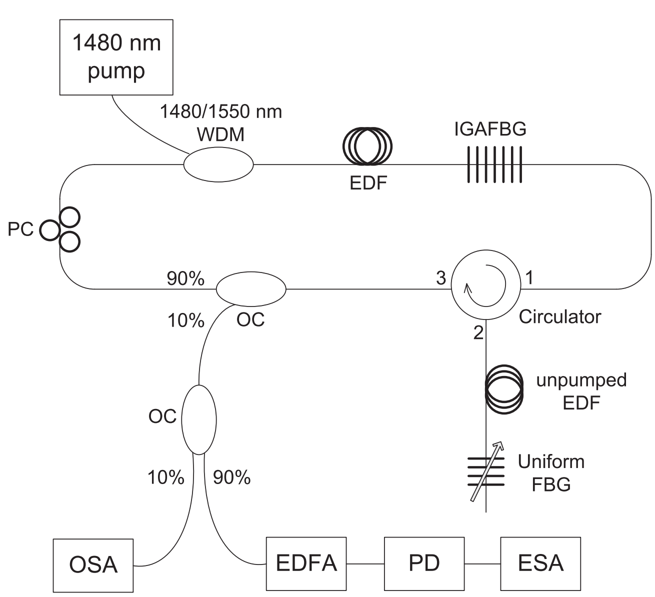

Fig. 2. Schematic diagram of the proposed fiber ring laser.

4. Discussion

It should be noted that, without the injection of the unpumped EDF as an SA, the SLM operation cannot be obtained in such a long cavity laser. The reason is explained as follows. In our experimental setup, the total cavity length of the fiber ring laser is approximately equal to 15 m when the SA is removed. Therefore, the free spectral range (FSR) of the laser cavity will be close to 13.3 MHz and to achieve an SLM operation, the 3 dB bandwidth of each of the two transmission bands in the IGAFBG must be smaller than twice the cavity FSR, which is around 26.6 MHz, corresponding to a 0.21 pm bandwidth. Although it is confirmed that the proposed IGAFBG consists of two ultra-narrow bandwidth transmission bands, their actual bandwidths cannot be determined using the 0.01 nm low-resolution OSA. Hence it is possible that the 3 dB bandwidths of the two transmission bands are greater than 0.21 pm, in which case no SLM operation can be achieved, as verified experimentally. However with the SA incorporated into the ring cavity, we were able to obtain an SLM operation successfully.

It is well known that, a large absorption coefficient of an EDF corresponds to a small optical power within the fiber laser and vice

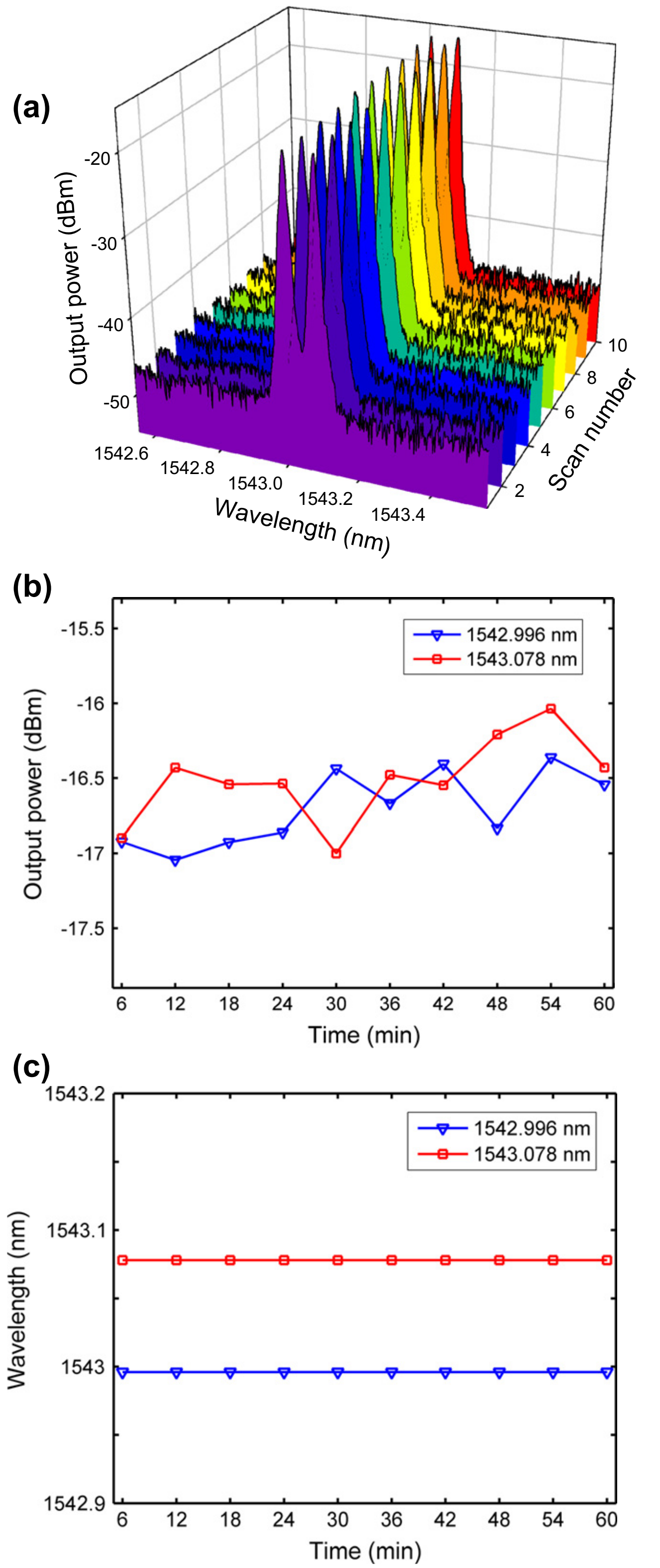

Fig. 4. (a) Lasing spectra taken at a 6-min interval over 1 h with dual-wavelength at 1542.996 and 1543.078 nm, (b) output power fluctuation and (c) emitting wavelength variation with scanning time.

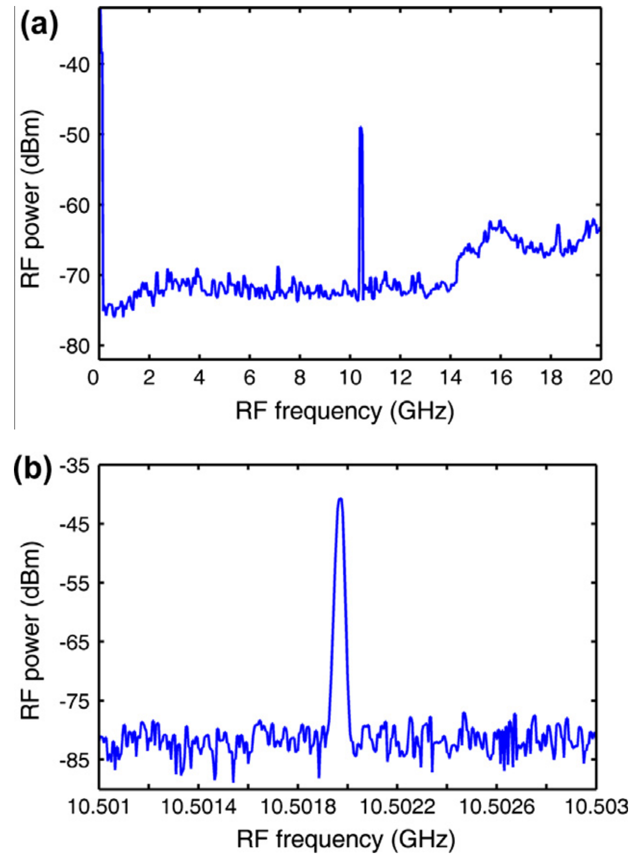

Fig. 5. Electrical spectrum of the beat signal. (a) 20 GHz span with resolution of 1 MHz and (b) 2 MHz span with resolution of 10 kHz.

versa. When lightwave propagates into the unpumped EDF, a standing wave can form within the fiber, which then distributes the spatial optical power periodically along the full length of the unpumped EDF. This leads to a periodical variation of the absorption coefficient along its length and hence a periodical refractive index variation along the unpumped EDF based on the Kramers–Kronig relation [16], thus inducing a weak FBG. In our experiment, the unpumped EDF has a low Er ion concentration of 3×10^{18} Er^{3+}/cm^3 and the average injection power is less than 20 mW, so that the average refractive index change is estimated to be less than 3×10^{-7} [17]. The 3 dB bandwidth of the induced FBG can then be calculated using $\Delta f = (c/\lambda)[2\Delta n/(n_{eff}\lambda)]\sqrt{(\Delta n/2n_{eff})^2 + (\Lambda/L_g)^2}$ [18,19], where c is the speed of light in vacuum, and $\Lambda = \lambda/(2n_{eff})$ is the grating period. Here we have used a wavelength λ = 1540 nm, a grating length L_g = 2 m, an effective refractive index n_{eff} = 1.48, and an average refractive index change $\Delta n < 3 \times 10^{-7}$ to estimate the 3 dB bandwidth of the self-induced FBG. The estimated 3 dB bandwidth is Δf < 14.3 MHz. With the cavity length of the fiber laser being approximately 19 m after incorporating the SA, which corresponds to a 10.5 MHz cavity FSR, it is obvious that the 3 dB bandwidth of the induced weak FBG is less than twice the laser cavity's FSR and hence an SLM operation with the dual-wavelength lasing is guaranteed.

Although in principle, an SLM operation can still be obtained by removing the SA from the cavity, it will require a short laser cavity length to ensure a sufficiently large cavity FSR. This can be achieved by shortening the length of the pumped EDF. However, such shortening will lead to an unexpected drop in the round-trip medium gain of the laser, resulting in a loss of lasing with time. One way to compensate for this loss of gain due to the shortened EDF is to replace it with a highly doped EDF. Such EDF has a high absorption coefficient which will cause its inherent temperature to increase thus affecting the stability of the fiber laser.

It may also be argued that, two cascaded uniform FBG at different Bragg wavelengths or a single sampled FBG can substitute the

IGAFBG filter to generate an SLM operation. Unfortunately, the two reflected peaks provided by the two cascaded FBGs can hardly achieve the small wavelength spacing of 0.082 nm, since the bandwidth of each uniform FBG is broad and the two reflected peaks will overlap when cascaded. Furthermore, IGAFBG has advantages over a sampled FBG, since it has no physical gaps in its grating structure [14].

By changing of the IGAFBG with different wavelength spacings, e.g., 0.146 nm, 0.1 nm and 0.07 nm [13], microwave signals at around 18.25 GHz, 12.5 GHz and 8.75 GHz can be generated in principle, which shows the flexibility of the proposed technique. Furthermore, as discussed in [14], the wavelength spacing between the two passbands of an IGAFBG could be continuously tuned through a tunable linear chirp on the grating, which may be realized by applying a strain gradient. The simulation result in [14] shows that it is possible to continuously change the wavelength spacing from 0.164 nm down to 0.14 nm for an IGAFBG. Hence, the proposed fiber laser may generate a tunable microwave signal from ~20.5 GHz to ~17.5 GHz.

5. Conclusions

We have demonstrated a stable dual-wavelength SLM laser based on an IGAFBG filter and a saturable absorber, with a wavelength spacing of 0.082 nm. A microwave signal at 10.502 GHz has been generated, whose stability is better than 1 MHz and a 3 dB bandwidth of less than 10 kHz at room temperature. It has potential applications in wireless communication, sensing systems and radio-over-fiber systems.

References

[1] J. Capmany, D. Novak, Microwave photonics combines two worlds, Nat. Photon. 1 (2007) 319–330.
[2] A.J. Seeds, K.J. Williams, Microwave photonics, J. Lightw. Technol. 24 (2006) 4628–4641.
[3] R.C. Williamson, RF photonics, J. Lightw. Technol. 26 (2008) 1145–1153.
[4] Y. Yao, X. Chen, Y. Dai, S. Xie, Dual-wavelength erbium-doped fiber laser with a simple linear cavity and its application in microwave generation, IEEE Photon. Technol. Lett. 18 (2006) 187–189.
[5] L. Xia, P. Shum, T.H. Cheng, Photonic generation of microwave signals using a dual-transmission-band FBG filter with controllable wavelength spacing, Appl. Phys. B 86 (2007) 61–64.
[6] S. Feng, O. Xu, S. Lu, T. Ning, S. Jian, Switchable single-longitudinal-mode dual-wavelength erbium-doped fiber ring laser based on one polarization-maintaining fiber Bragg grating incorporating saturable absorber and feedback fiber loop, Opt. Commun. 282 (2009) 2165–2168.
[7] W. Liu, M. Jiang, D. Chen, S. He, Dual-wavelength single-longitudinal-mode polarization-maintaining fiber laser and its application in microwave generation, J. Lightw. Technol. 27 (2009) 4455–4459.
[8] X. Chen, J. Yao, Z. Deng, Ultranarrow dual-transmission-band fiber Bragg grating filter and its application in a dual-wavelength single-longitudinal-mode fiber ring laser, Opt. Lett. 30 (2005) 2068–2070.
[9] X. Chen, Z. Deng, J. Yao, Photonic generation of microwave signal using a dual-wavelength single-longitudinal-mode fiber ring laser, IEEE Trans. Microw. Theory Tech. 54 (2006) 804–809.
[10] D. Chen, H. Fu, W. Liu, Y. Wei, S. He, Dual-wavelength single-longitudinal-mode erbium-doped fibre laser based on fibre Bragg grating pair and its application in microwave signal generation, Electron. Lett. 44 (2008) 459–461.
[11] J.L. Zhou, L. Xia, X.P. Cheng, X.P. Dong, P. Shum, Photonic generation of tunable microwave signals by beating a dual-wavelength single longitudinal mode fiber ring laser, Appl. Phys. B 91 (2008) 99–103.
[12] X. He, X. Fang, C. Liao, D.N. Wang, J. Sun, A tunable and switchable single-longitudinal-mode dual-wavelength fiber laser with a simple linear cavity, Opt. Exp. 17 (2009) 21773–21781.
[13] B. Lin, H. Zhang, S.C. Tjin, D. Tang, J. Hao, C.M. Tay, S. Liang, Inverse-Gaussian apodized fiber Bragg grating for dual wavelength lasing, Appl. Opt. 49 (2010) 1373–1377.
[14] B. Lin, S.C. Tjin, N.Q. Ngo, Y. Song, S. Liang, L. Xia, M. Jiang, Analysis of inverse-Gaussian apodized fiber Bragg grating, Appl. Opt. 49 (2010) 4715–4722.
[15] T. Erdogan, Fiber grating spectra, J. Lightw. Technol. 15 (1997) 1277–1294.
[16] S. Fleming, T. Whitley, Measurement and analysis of pump dependent refractive index and dispersion effects in erbium-doped fiber amplifiers, IEEE J. Quant. Electron. 32 (1996) 1113–1121.
[17] E. Desurvire, Erbium-doped Fiber Amplifiers: Principles and Applications, John Wiley & Sons, 1994, pp. 295–302.
[18] A. Othonos, K. Kalli, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunication and Sensing, Artech House, 1999.
[19] K. Zhang, J.U. Kang, C-band wavelength-swept single-longitudinal-mode erbium-doped fiber ring laser, Opt. Exp. 16 (2008) 14173–14179.