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Opto-VLSI-based tunable single-mode fiber laser

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Abstract: A new tunable fiber ring laser structure employing an Opto-VLSI processor and an erbium-doped fiber amplifier (EDFA) is reported. The Opto-VLSI processor is able to dynamically select and couple a waveband from the gain spectrum of the EDFA into a fiber ring, leading to a narrow-linewidth high-quality tunable laser output. Experimental results demonstrate a tunable fiber laser of linewidth 0.05 nm and centre wavelength tuned over the C-band with a 0.05nm step. The measured side mode suppression ratio (SMSR) is greater than 35 dB and the laser output power uniformity is better than 0.25 dB. The laser output is very stable at room temperature.

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1. Introduction

The development of tunable laser sources featuring single longitudinal hopping-free mode and narrow linewidth around 1.55-μm has attracted considerable interest in applications such as optical communications, optical sensing, optical signal processing, spectroscopy and instrumentation. Compared to tunable semiconductor lasers, fiber lasers have potential

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advantages of narrow linewidth, low intensity noise, high output power, reduced packaging cost, and inherent compatibility with fiber optics. An additional attractive feature of fiber-based laser sources is their large gain bandwidth across the S-, C- and L-bands, which enables considerable flexibility in wavelength/bandwidth selection and allocation in dynamic optical systems and networks. Single-mode fiber lasers have widely been investigated for optical communication applications [1–9]. In particular, erbium-doped fiber lasers offer several advantages, such as the broad emission spectrum and homogeneously-broadened gain characteristics, resulting in a high side-mode suppression ratio. However, because of their very long cavity length, single-mode fiber ring lasers exhibit multimode oscillation, mode competition and mode hopping, making the selection and wavelength tuning inaccurate.

Several reported approaches to realizing single-mode tunable fiber ring lasers have been reported, including the use of fiber Bragg gratings (FBGs) [1–3], acousto-optic tunable filter [4,5], and Fabry-Perot or etalon filters [6–9]. Since an FBG can be tuned easily through either heating or applying strain along the FBG, FBG-based fiber ring lasers are subject to environmental changes, which result in high packaging cost and limited tuning range. Tunable fiber lasers based on acousto-optic and Fabry-Perot filters generally require additional matching components such as Fabry-Perot laser diodes, saturable absorber-based autotracking filters, making them complex and expensive for commercial use. It is important to note that a fiber ring laser structure based on an integrated-optic acoustically tunable optical filter has been reported, demonstrating a 40-nm continuously tuning range, a 10 kHz laser linewidth, and a wavelength switching speed of up to 100 kHz which is much faster than the speeds attained by tunable lasers based on FBGs, Fabry-Perot filters, and Liquid-Crystal-based tunable filters [5].

In this paper, we propose and demonstrate a novel tunable fiber laser employing an Opto-VLSI processor, which arbitrarily selects narrowband optical signals from the amplified spontaneous emission (ASE) spectrum of an EDFA and injects them into a recirculating fiber ring to generate laser signals at arbitrary wavelengths. The Opto-VLSI-based tunable fiber laser has a linewidth as small as 0.05 nm and a tuning step of about 0.05 nm. It is motionless and can be tuned electronically (via software) over the gain bandwidth of the EDFA.

2. Opto-VLSI processor

An Opto-VLSI processor consists of an array of electro-optic cells independently addressed by a Very-Large-Scale-Integrated (VLSI) circuit to generate a reconfigurable, reflective digital holographic diffraction grating capable of steering an optical beam along arbitrary directions [10]. It comprises a silicon substrate, evaporated aluminum mirror that acts as the reflective electrode, liquid crystal (LC), transparent Indium-Tin Oxide (ITO) electrode and a glass cover. A quarter-wave plate (QWP) layer between the liquid crystal and the VLSI backplane can also be used for polarization insensitive operation [11]. By driving the reflective aluminum electrodes (via the VLSI circuit) with a voltage profile, a steering digital phase hologram (or blazed grating) can be synthesized, and the diffraction angle, α_m, is given by:

$$\alpha_m = \arcsin(\frac{m\lambda}{d}) \tag{1}$$

where m is the diffraction order (here only first order is considered), λ is the vacuum wavelength, and d is the grating period.

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3. Structure of Opto-VLSI-based tunable fiber laser

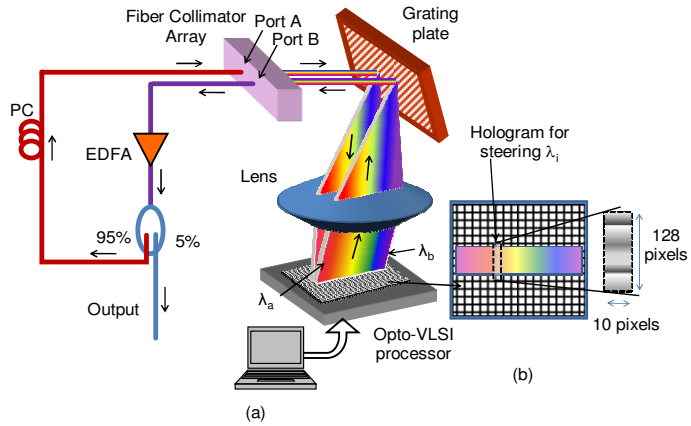

Fig. 1. Opto-VLSI-based tunable fiber laser structure. PC: polarization controller.

The proposed Opto-VLSI-based tunable fiber ring laser structure is shown in Fig. 1. It employs an EDFA, a 5:95 optical coupler, a polarization controller, and a fiber collimator pair (Port A and Port B). 95% of broadband ASE spectrum initially generated by the EDFA is routed to the Opto-VLSI processor through Port A of the fiber collimator array. A polarization controller (PC) is used to align the ASE polarization so that the diffraction efficiency of the Opto-VLSI processor is maximized, and also to enforce single-polarization laser operation. The grating plate demultiplexes the collimated broadband ASE signal along different directions. The lens between the Opto-VLSI processor and the grating plate has a focal length of 10 cm and is placed at 10 cm from the grating plate so that the dispersed ASE wavebands are deflected along the same direction and mapped onto the surface of an Opto-VLSI processor as illustrated in Fig. 1(a). By driving the Opto-VLSI processor with an appropriate steering phase hologram, any waveband of the ASE spectra can be routed to and coupled into Port B of the fiber collimator array (see Fig. 1(b)), and the others are dropped out with dramatic attenuation (according to Eq. (1)). The selected wavebands that are coupled into Port B are amplified by the EDFA, leading, after several recirculations, to single-mode laser generation. In this way, the fiber laser can be tuned by simply uploading appropriate phase holograms that drive the various pixels of the Opto-VLSI processor.

It is important to notice that the ability of the Opto-VLSI based tunable fiber laser architecture (shown in Fig. 1) to tune the output laser wavelength without the need for moving parts or heating makes it very reliable for commercial use.

4. Experimental results

In the experiments, the EDFA was a C-band amplifier having a small signal gain of 14 dB, and a gain spectrum shown in Fig. 2. The EDFA's pump laser was driven with a current of 400 mA. A 256-phase-level 512 × 512-pixel Opto-VLSI processor of pixel size 15 µm with an insertion loss of about 0.5 dB was used. The spacing between the fiber collimator elements (Port A and Port B) was 3 mm, and the insertion loss and return loss for the two ports were 0.6 dB and 55 dB, respectively. An optical spectrum analyzer with 0.01 nm resolution was used to monitor the laser output power generated at the 5% output port of the optical coupler (Fig. 1). The ASE signal was collimated at 0.5 mm diameter, and a blazed grating plate, having 1200 lines/mm and a blazed angle of 70° at 1530 nm, was used to demultiplex the ASE signal and map onto the active window of the Opto-VLSI processor through a lens of focal length 10 cm placed at 10 cm from the grating plate. A Labview software was developed to generate the optimized digital holograms that steer the desired waveband and couple into the collimator Port B.

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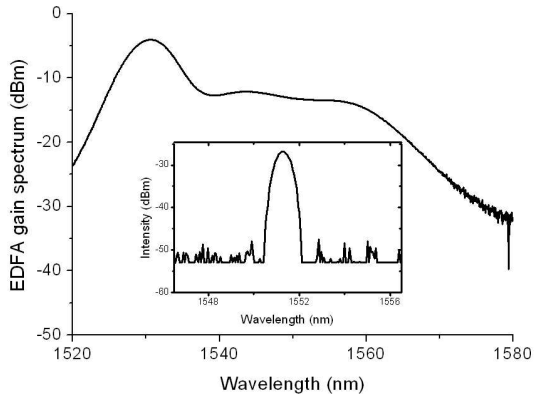

Fig. 2. Amplified spontaneous emission (ASE) noise from the EDFA. The inset is an example of a waveband selected by the Opto-VLSI processor.

Some important parameters were measured when the optical loop was open. The ASE noise signal of the EDFA is shown in Fig. 2. The gain spectrum of the EDFA was linearly mapped along the active window of the Opto-VLSI processor. The inset of Fig. 2 is an example that illustrates the selection and coupling of an arbitrary waveband into Port B by uploading a phase hologram onto the Opto-VLSI processor. The measured total insertion loss from Port A to Port B was around 12 dB, which was mainly due to (i) the lens reflection loss; (ii) the blazed grating loss; and (iii) diffraction loss and insertion loss of the Opto-VLSI processor.

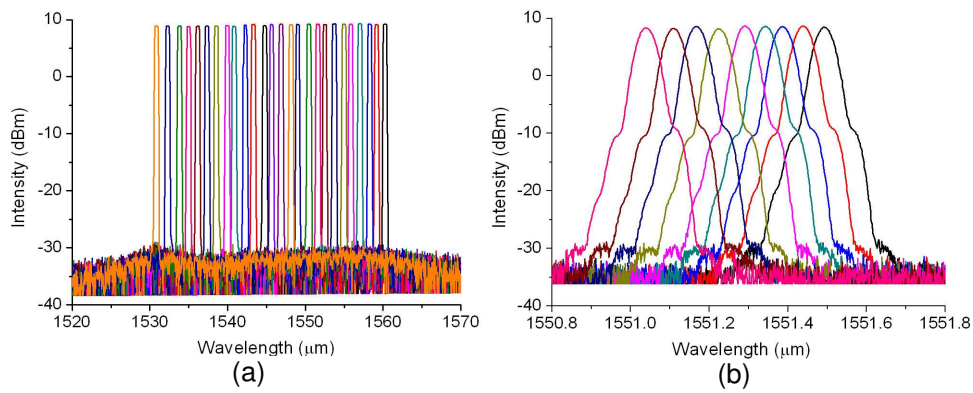

Fig. 3. Measured outputs of the Opto-VLSI-based fiber laser. (a) Coarse wavelength tuning over C-band, and (b) fine wavelength tuning.

After the optical loop was closed, the Opto-VLSI processor was driven by different phase holograms, each corresponding to a single-mode lasing at a specific wavelength. Each selected waveband experienced a high gain by the EDFA in comparison to the gains experienced by the other ASE wavebands. Figure 3(a) shows the measured outputs of the Opto-VLSI-based fiber laser and demonstrates an excellent tuning capability over the C-band through the generation of 8 × 512 phase holograms at different position along the active window of the Opto-VLSI processor. The linewidth of the tunable laser was about 0.05 nm, compared to 0.5 nm when the optical loop was open (see the inset in Fig. 2). The measured side-mode suppression ratio (SMSR) was greater than 35 dB and the output power ripple was less than 0.25 dB over the entire C-band. The small ripples in the laser output power levels can be attributed to two main reasons, namely, (i) the EDFA worked in deep saturation, which clips the lasing output power; and (ii) the excellent stability and uniformity of the Opto-VLSI processor in steering and selecting wavebands over the whole C-band.

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Figure 3(b) shows the measured laser outputs when fine wavelength tuning was performed by shifting the center of the phase hologram by a single pixel across the active window of the Opto-VLSI processor. The wavelength tuning step was around 0.05 nm. This corresponds to the mapping of 30 nm bandwidth of ASE spectrum of the EDFA across the 512 pixels (each of 15 μm size). Note that the tuning resolution can be made smaller by using an Opto-VLSI processor with a smaller pixel size. Note that the shoulders on both sides of the laser spectrum may be due to self-phase modulation or other nonlinear phenomena arising from a high-level of the output power [12].

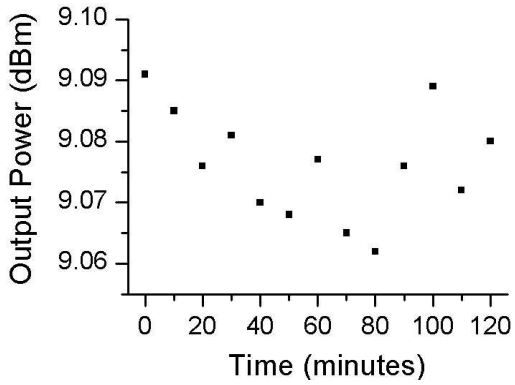

Fig. 4. Output power fluctuation for the Opto-VLSI-based tunable fiber laser.

Note also that the measured crosstalk between Port A to Port B, defined as the ratio of the unselected ASE signal to the power of the waveband selected by the Opto-VLSI processor, was less than −55 dB. This crosstalk level, which contributes to the background level of the laser output and SMSR, can be reduced by (i) increasing the spacing between Port A and Port B, (ii) improving the imaging quality of the lens, (iii) increasing the collimated beam diameter, and (iv) reducing the pixel size of the Opto-VLSI processor.

Finally, the laser exhibited very stable operation at room temperature when it was turned on for different periods of time ranging from a few hours to a few days. Figure 4 shows that the output power fluctuation is within 0.03 dB during a period of 2-hour observation.

5. Conclusion

A novel tunable Opto-VLSI-based fiber ring laser that can operate over the whole EDFA gain bandwidth has been proposed and experimentally demonstrated. The tunable laser employs a reconfigurable Opto-VLSI processor for wavelength selection, an EDFA as a gain medium, a grating plate for wavelength demultiplexing and optics for optical beam mapping. Experimental results have shown that the tunable fiber laser has an SMSR larger than 35 dB, an output power uniformity of 0.25 dB over the entire C-band, a linewidth as narrow as 0.05 nm, a wavelength tuning resolution as small as 0.05 nm, and excellent stability at room temperature.

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