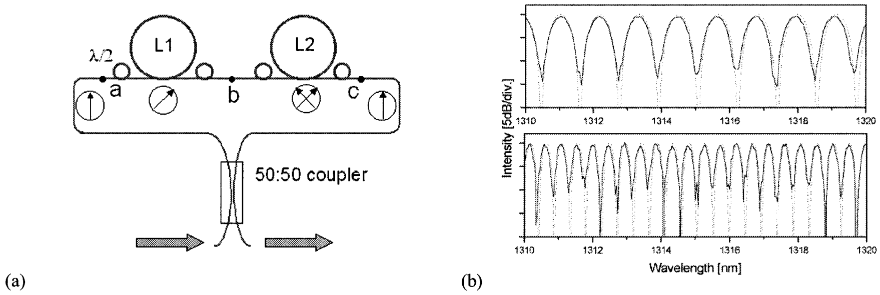


WJ1 Fig. 2. (a) Tunable Sagnac loop filter setup. The arrows inside circle represent the relative angle directions of the fast axis of HB fiber and the plane of Sagnac loop. (b) Calculated and measured transfer functions with different wavelength period. The solid lines are for measured transfer function and the dot lines are for calculated transfer function.

by varying the effective length of Solc fiber section, which was developed previously in our lab.[5]

As shown in Fig. 2 (a), the tunable dual-section HB fiber Sagnac loop filter is composed with a 50:50 coupler centered at 1310 nm and two sections of HB fiber, L1 and L2, with the all-fiber half wave plates, λ/2. As changing the fast axis direction angles of Solc fiber sections in respect to the plane of the Sagnac loop, we can vary the whole effective length discretely[5] and, thus, the wave spacing of periodic spectrum is also tuned as the function of the effective length of fiber. For the relative angle changes, $\pi/4, 0, -\pi/4$, at the position of a, b, and c in Fig. 2 (a), respectively, we can know the whole effective length is L1 + L2, and, in the other way, the combination of relative angles, $\theta(a) = \pi/4, \theta(b) = -\pi/2$, and $\theta(c) = \pi/4$, would induce it to be L1 – L2. Because the wavelength period, $\Delta\lambda$, is simply the function of total beat length in the cavity, it can be written as:

$$\Delta\lambda = \frac{\lambda^2}{l\Delta n} \tag{1}$$

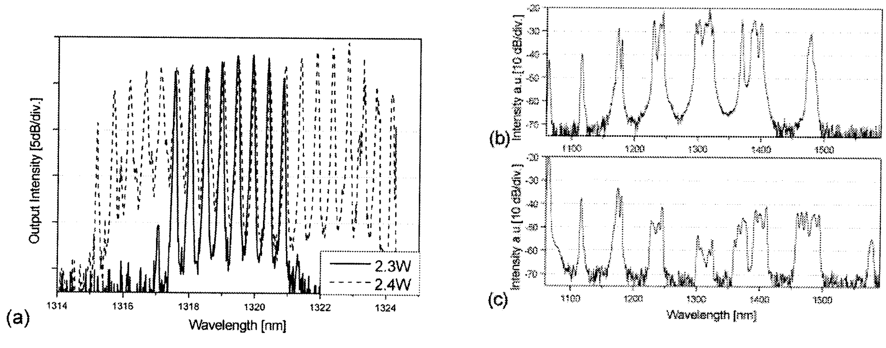
where λ is the operation wavelength, Δn is the difference of the effective mode indices in the two orthogonal polarization modes, l is effective length of the fiber, which could be varied as L1 + L2 or L1 – L2.

When the half wave polarization controllers were optimally positioned, different periodic filtering spectra are appeared as shown in Fig.2 (b). The lengths of each Solc HB fiber, L1 and L2, were 7 m and 3 m, respectively. For the upper and lower cases in Fig.2 (b), measured values of wavelength period were 1.15 nm and 0.46 nm, respectively. The 0.2 nm resolution bandwidths of optical spectrum analyzer were used to measure with the white light source. Numerical results around 1310 nm, corresponding to the measurements, are also shown by the dot lines in Fig. 2 (b) with the assumption of L1 – L2 = 3.98, L1 + L2 = 9.90, and Δn = 0.000375. With the similar procedure, adding more Solc fiber sections in the Sagnac loop can increase the possible numbers of different wavelength period. A higher order tunable filter can be constructed by connecting the first order tunable HB fiber Sagnac loop filters in cascade.

3. Experiment results

Fig. 3 (a) shows the multi-wavelength output of 0.43 nm spacing from the output of WDM1. Around the threshold of lasing, 2.3 W, we can see 8 wavelength output with an extinction ratio higher than 20 dB. The wavelength spacing of each output peak is corresponding to the wavelength period of fiber Sagnac loop filter. As the pump power was increased to 2.4 W, the greater number of wavelength channel was achieved with more than 20 wavelengths ranging from 1315 nm to 1325 nm. Using the tunable HB fiber Sagnac loop filter in Fig 2 (b), two distinct channel spacing could be achieved.

Increasing the pump power above the lasing threshold around 1.31 μm, the Raman generation becomes saturated, providing the next order Raman stokes. Fig. 3 (b) shows the typical cascaded Raman spectrum up to 6th order stokes for the pump power of 7.8 W, where the output power of the all the stokes wave was measured to be approximately 270 mW. With the simpler ring configuration with the 4.3 km DSF, Sagnac filter, and the WDM1 only, the 7th order Raman stokes generation around 1.57 μm can also be achieved as can be seen in Fig. 3 (c). The threshold power for the generation of 7th order Raman stokes wave was ~8 W. In this case the total output power of stokes waves was measured to be approximately 490 mW. Thus by operating at different pump power levels, the multi-wavelength source can be realized in different wavelength regimes.



WJ1 Fig. 3. (a) Multi-wavelength output spectra of 4th stokes wave for the pump powers of 2.3 W and 2.4 W. (b) Cascaded Raman spectrum from the output of WDM2 for the pump power of 7.8 W. (c) Cascaded Raman spectrum from the output of WDM1 for the pump power of 8.2 W.

4. Conclusions

We have experimentally demonstrated a multi-wavelength fiber Raman source based on a tunable HB fiber Sagnac loop filter. Using the novel scheme, we have demonstrated a generation of a broad cascaded stokes waves with wavelength between 1.12 ~ 1.57 μm and the generation of approximately 20 wavelength channels within the 4 th order stokes waves. By adjusting the pump power and the cavity, the multi-wavelength operation is possible within a particular stokes waves or all the stokes waves. Such multi-wavelength laser source is expected to be useful in many applications including the WDM and sensing area.

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WJ2 **1:45 pm**

Power equalization with optical feedback in a 52 wavelength SOA ring laser source

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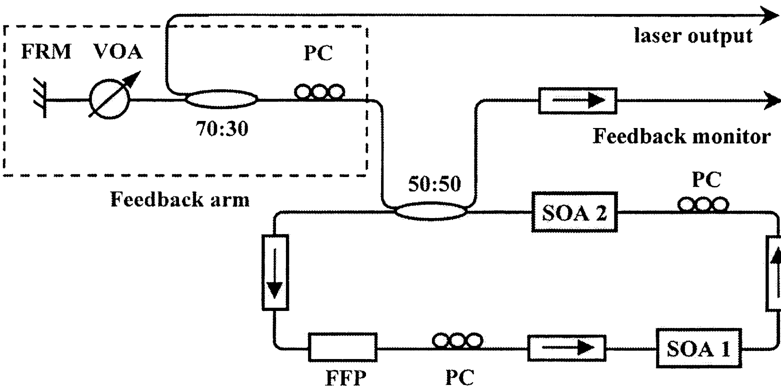
1. Introduction

Very high capacity WDM systems are now a commercial reality and as the channel count has con-



WJ2 Fig. 1. Experimental setup of the multiwavelength laser source.

tinued to increase, so has the interest in multi-wavelength laser sources for a number of potential applications such as passive and active WDM component characterization and transmission. Multi-wavelength sources may be used instead of a number of discrete laser sources or tunable laser sources, to reduce cost, electrical driver real estate and measurement procedure complexity. For example multi-wavelength laser sources are ideal for optical amplifier characterization where the gain profile must be saturated across its whole spectrum for reliable measurements or PMD and PDL measurements that are usually carried out with tunable sources. So far a number of techniques have been demonstrated to obtain multi-wavelength operation including spectrum slicing in LED's,[1] amplified spontaneous emission from EDFAs,[2] supercontinuum generation in fiber[3] and femtosecond pulses.[4] Multiwavelength operation was also been demonstrated with a liquid nitrogen cooled EDF laser oscillator with a fiber Lyot filter[5] and an EDF laser with an intracavity grating.[6] More recently multi-wavelength operation has been obtained in semiconductor optical amplifier (SOA) cavities.[7–9]

In the present communication we propose a novel, to our knowledge, technique for obtaining power equalization and to extend the oscillating bandwidth of a multi-wavelength SOA ring laser. The technique employs a single-pass, optical feedback from the laser output as self-saturating signal. We report the demonstration of a stable laser source capable of generating 52 wavelengths with less than 0.3 dB power variation between them (standard deviation value), nominal wavelength spacing of 50 GHz, 500 MHz linewidth and better than 32 dB extinction. The source operates at room temperature, uses two SOAs to provide gain and a fiber Fabry-Perot filter for wavelength comb generation.

2. Experiment

Room temperature, multi-wavelength oscillation as well as power equalization across the oscillating wavelengths by means of self-saturation are a result of the heterogeneously broadened structure of a SOA. A laser cavity built with a single SOA (SOA 1) oscillates at slightly longer wavelengths when the signal is coupled to its high gain axis (TE) as opposed to its low gain axis (TM). It is therefore possible to extend the oscillating bandwidth by coupling the signal to both axes. The oscillating bandwidth and average power from the source can be further increased by introducing a second SOA (SOA 2) with a slightly offset peak gain. Power equalization across the broad oscillating spectrum may then be efficiently effected by providing a self-saturating signal from the output of the source.

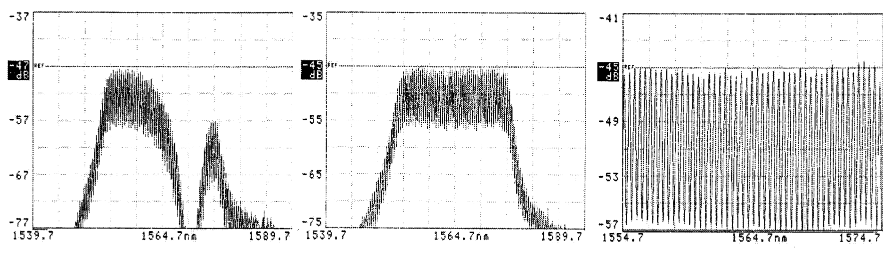
Figure 1 shows the experimental setup of the multi-wavelength laser source as it was implemented. Gain was provided by two bulk, 500 μm long, commercially available (Opto Speed, S.A.), InGaAsP/InP ridge waveguide SOAs, with facets angled at 10^0 and antireflection coated. SOA 1 provided peak small signal gain of 22 dB at 1530 nm, with 1.5 dB polarization dependence when driven with 250 mA dc current and SOA 2 provided peak small signal gain of 23 dB at 1522 nm, with 1.9 dB polarization dependence when driven with a 250 mA dc current. Polarization controllers were used at their input port of the SOAs to adjust the input state of polarization. Isolators were used at the input and output of the two SOAs to ensure unidirectional oscillation in the ring and to restrict the saturation effect of the feedback signal to SOA 2 only. The profile of the oscillating spectrum was determined by a fiber Fabry-Perot (FFP) filter, with free spectral range 47.75 GHz, finesse 8.1 and 1.7 dB insertion loss. The output signal was obtained from a 50:50 fused fiber coupler and part of it was returned back to the laser via a Faraday rotator mirror (FRM) through a 70:30 coupler. A variable optical attenuator (VOA) was used in the feedback arm to adjust the optical power back into the oscillator.

The recirculating signal experiences more losses travelling from SOA 2 to SOA 1 than from SOA 1 to SOA 2, and so the SOA 1 must be driven at a lower current than SOA 2 in order to provide a wide oscillating spectrum. Correspondingly SOA 2 is deeply saturated resulting in gain compression and an oscillating spectral profile, that is strongly featured. By providing an appropriate level of this featured spectral profile as saturating signal in the opposite direction to the lasing signal, equalization of the power of the oscillating wavelengths may be achieved. Essentially the more intense wavelengths provide higher power in the saturating signal and larger saturation in the SOA. Optimization of the cavity losses, the optical power of the feedback signal and adjustment of the drive currents for the two SOAs, can result in a broad, uniform oscillating spectrum.

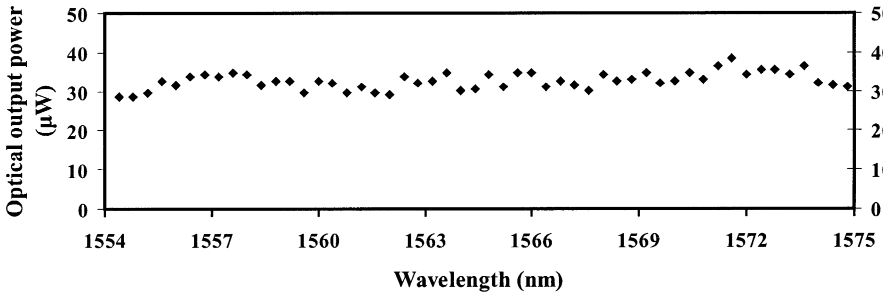
3. Results and discussion

Figure 2 shows the oscillating spectra of the laser source with the drive currents for SOA 1 and SOA 2 adjusted at 182 mA and 215 mA respectively. Figure 2(a) displays the output in the absence of the feedback and shows a broad but highly featured profile. Figure 2(b) shows that the introduction of 235 μW of signal into SOA 2 from the feedback arm, equalizes the power spectrum and broadens it to nearly 21 nm. The output of the laser consists of 52 oscillating wavelengths and figure 2(c) shows in more detail 49 of these 52 oscillating wavelengths. The total output power was 1.7 mW and the standard deviation of the power between the oscillating wavelengths was 0.3 dB.

The power distribution of the 52 most intense lines is shown in figure 3. The FWHM of each oscillating wavelength was measured with an optical spectrum analyzer and was found to be 0.16 nm, which is the resolution limit of the instrument. In order to improve on the accuracy, each line was isolated with a second fiber Fabry-Perot (FFP) filter (5.2 GHz bandwidth) and was detected by a photodiode. The resulting beat spectrum of the cavity modes was measured with an RF spectrum analyzer. With this technique and assuming a Lorentzian lineshape, the oscillating width of each wavelength line was found to be 500 MHz. Using the second fiber Fabry-Perot filter we have also measured the power level of each wavelength line and the noise background level in order to calculate the extinction ratio between the lines. The extinction was found to be 32 dB, but it is expected to be significantly better because the measurements were made after signal amplification in an EDFA. Both linewidth and extinction ratio can be further improved by using a narrower Fabry-Perot in the cavity in which case the source could in principle be used for transmissions. It should be noted that if a single SOA is used in the cavity, then a flat oscillating spectrum of 20 nm width can be obtained, resulting in an optical spectrum of 50 simultaneously oscillating wavelength lines. In this configuration the wave-



WJ2 Fig. 2. Optical spectrum of the multiwavelength laser (a) without optical feedback; (b) with optical feedback (sweepwidth 5 nm/div); and (c) with optical feedback (sweepwidth 2 nm/div).



WJ2 **Fig. 3.** Power distribution in output wavelength channels.

length linewidth was 600 MHz, the extinction between channels was greater than 30 dB and the total output power was 1 mW.

4. Conclusion

In summary, we have demonstrated a simple and stable, multi-wavelength laser source. It combines two semiconductor optical amplifiers and a fiber Fabry-Perot filter to generate 52 simultaneously oscillating wavelengths across 21 nm with a flat output spectrum. The power equalization and the broadening of the oscillating spectrum was achieved by means of adjusted, single-pass optical feedback of its output back into the source. The power standard deviation between the lines is less than 0.3 dB, the extinction between them was greater than 32 dB and their linewidth was calculated to be 500 MHz. The source may be useful as a relatively inexpensive source for passive and active component characterization.

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WJ3 2:00 pm

Multiwavelength 'Single-Mode' Erbium Doped Fiber Laser for FFH-OCDMA Testing

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Introduction

Optical code division multiple access (OCDMA) has recently raised a lot of interest for the development of access networks. Systems have been proposed based on direct sequence or frequency-encoding approaches.[1,2] Fast frequency hopping (FFH) has also been considered to increase the system capacity using two-dimensional codes.[3] In all these cases, fiber Bragg gratings technology is simple and reliable for the realization of the encoders. In a frequency-encoding system, interrogation of the encoder is traditionally performed by a broadband source. Incoherent sources like LEDs or superfluorescent emission from an erbium-doped fiber (EDF) can be used, but their output power is limited and the detected signal suffers from a high level of beat noise. Another approach is to use a short pulse laser, which is a rather complex system. If the encoder frequency bands are equally spaced, for example anchored on the 100 GHz ITU grid, an alternative solution is to use multiwavelength lasers, for example DFB laser arrays. For testing purpose, a single fiber laser source emitting multiple wavelengths, single-mode at each wavelength, is also of great interest.

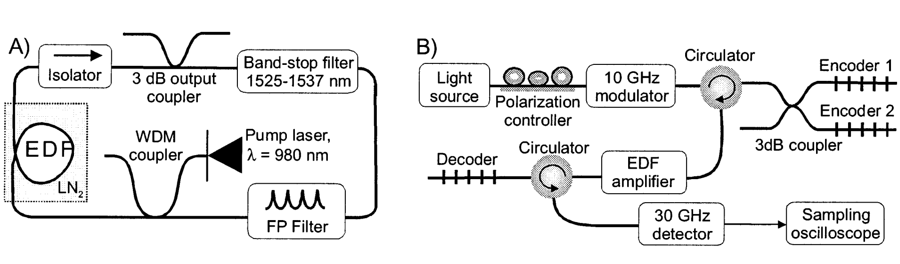
To realize a multiwavelength EDF laser, it is necessary to overcome its typical homogenous line broadening. Multiwavelength operation has been demonstrated by using a two-core fiber which allows for macroscopic hole burning,[4] or by using of a frequency shifter in the resonant laser cavity which perturbs the laser build-up mechanism.[5] However, the most straightforward technique remains the liquid nitrogen cooling of the EDF.[6,7] The gain medium can then be considered as having a dominantly homogenous bandwidth of only 0.5 nm, giving possibility of single-frequency oscillation at each wavelength. Two cavity configurations are mostly used, either a Fabry-Perot (FP) linear configuration[7] or a traveling wave ring configuration.[6] To achieve single-mode wavelengths spaced by 50 GHz, a simple FP cavity has to be less than 2 mm long resulting in low output power.[7] Although multiwavelength operation of a ring EDF lasers was demonstrated,[6] to our knowledge, there are no report of 'single-mode' multiwavelength bands in this configuration.

In this paper, we first demonstrate the 'single-mode' operation of a multiwavelength EDF ring laser. The EDF is cooled to liquid nitrogen temperature and a bulk FP filter is incorporated in the cavity as a frequency selective element. We then compare the performance of a high speed FFH-OCDMA tested with the developed multiwavelength laser source and a traditional incoherent broadband source.

Design and Methods Used

The fiber laser set-up is shown in Fig. 1. The 3 m long EDF (Er concentration of 4370 ppm weight) was immersed into liquid nitrogen (LN_2) and was pumped by a copropagating 980 nm laser diode with a maximum power of 120 mW. In order to ensure traveling-wave operation and reduce noise, a single-stage polarization insensitive isolator was used. The filter, which selects the laser lines, was a bulk-optics FP etalon with free spectral range of 99.9 GHz and finesse of 104. The minimum transmission losses of the FP with collimating optics and connecting fibers were measured to be 5 dB. In series with this filter, we placed a wideband fiber Bragg grating filter (TeraXion, Inc.) cutting the EDF gain peak at 1535 nm (10 dB attenuation over 1525–1537 nm). The 3-dB output coupler was placed after the EDF and the isolator. All the laser cavity components were fusion spliced. The total cavity length was 9 m and the total cavity losses were 9 dB. The length of EDF was adjusted in order to cover the spectral range where the available FFH-OCDMA was operating.[8] Using shorter fiber lengths, the laser operating range can be tuned towards shorter wavelengths and vice-versa. To increase laser stability, it was packaged into a box with a fiber output terminated by a FC/PC connector.

The FFH-OCDMA set-up is schematically shown in Fig. 1, more details can be found in.[8]



WJ3 **Fig. 1.** Multiwavelength fiber laser set-up (A) and FFH OCDMA (B).