Optical and Quantum Electronics **35:** 865–872, 2003.

23 Wavelength with 100 GHz spacing comb generator source

K. VLACHOS[1,*], TON KOONEN[2], G. THEOPHILOPOULOS[3] AND H. AVRAMOPOULOS[3]
[1]Bell Laboratories, Lucent Technologies, Larenseweg 50, 1200BD Hilversum, The Netherlands
[2]COBRA Institute, Eindhoven University of Technology, Den Dolech 2, 5600MB Eindhoven, The Netherlands (E-mail: a.m.j.koonen@tue.nl)
[3]Photonics Communication Research Laboratory, National Technical University of Athens, 9 Iroon Polytechniou str., Zografou Campus, GR15773, Greece (E-mail: hav@cc.ece.ntua.gr)
(*author for correspondence: E-mail: kvlachos@lucent.com)

Received 8 November 2002; accepted 28 January 2003

Abstract. Simultaneous oscillation of 23 wavelengths, spaced at 100 GHz, is demonstrated from a single source using a semiconductor optical amplifier linear cavity. The wavelength comb is generated from an intra cavity, fiber implemented Lyot filter. Each oscillating wavelength has a linewidth of 12.5 GHz and the maximum power variation between the 23 wavelengths was less than 3 dB.

Key words: comb filter, linear cavity, multi-wavelength source, polarization maintaining fibre, semiconductor optical amplifier

1. Introduction

In the recent past there has been an intense effort in the development and deployment of very high capacity DWDM systems. As the number of wavelengths continues to increase beyond a few hundred, the cost of the laser transmitters and electronic drivers will start to make a significant part in the cost of the system. With this in mind, a number of alternative techniques of obtaining multi-wavelength operation from single laser sources have been investigated. One of the successful techniques is that of spectrum slicing and this has been applied to LED's (Reeve *et al.* 1988), superluminescent diodes (Wagner *et al.* 1990), amplified spontaneous emission from EDFAs (Lee *et al.* 1993), supercontinuum generation in fiber (Morioka *et al.* 1995) and femtosecond pulses (Lewis *et al.* 1998; Boivin *et al.* 1999; Collings *et al.* 1999). A different approach has also been investigated, in which multi-wavelength oscillation was obtained in a semiconductor optical amplifier (SOA) laser with the use of an intra-cavity grating (Shi *et al.* 1998) and Fabry–Perot etalon filter (Papakyriakopoulos *et al.* 1999; Vlachos *et al.* 2000).

Recently, 24 line operation was demonstrated with a liquid nitrogen cooled EDFA laser oscillator that used a Lyot-type comb fiber filter (Park *et al.* 1996). In the present communication we report the demonstration of a stable laser source capable of generating 23 wavelengths, with 100 GHz line spacing, 12.5 GHz line width, 17 dB extinction between lines and less than 3 dB power variation between them. The source operates at room temperature and uses a SOA for gain and a fiber Lyot filter for wavelength comb generation. It was also possible to extend the number of lines to more than 30 at the expense power equalization between them.

2. The Comb generating filter and multi-wavelength source

Fig. 1 shows the polarization maintaining (PM) fiber Lyot filter. It consists of a length L of PM fiber, placed between polarizers aligned at 45° with respect to the birefringent axes of the PM fiber. Due to the different propagation constants of the two axes of the birefringent fiber, a squared cosinusoidal filtering function is imposed on light travelling through the structure. The free spectral range is determined by the length and the birefringence of the PM fiber. The single-pass transmission function through the filter is given by

$$T = \frac{1}{4}|\exp(-\mathrm{j}\beta_x L) + \exp(-\mathrm{j}\beta_y L)|^2 = \cos^2\left[\frac{(\beta_x - \beta_y)\cdot L}{2}\right],$$

where β_x and β_y the propagation constants through the axes of the PM fiber. The free spectral range of the filter is given by

$$\delta\lambda_{\mathrm{FSR}} = \frac{B\cdot\lambda}{L},$$

where B is the beat length of the PM fiber.

With commercially available PM fiber of 3 mm beat length, 5.77 m of fiber are required to construct a comb filter with 100 GHz line spacing. Distinguishing features of the filter that result from its cosine-squared transmission function, are the low single pass finesse (2) but very high extinction at the

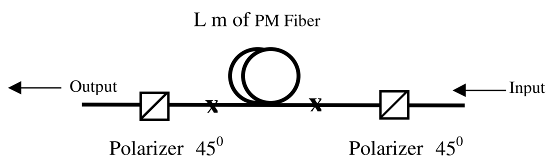

Fig. 1. The PM fiber, comb-generating filter.

center of the rejected wavelengths. The filter is attractive for wavelength comb generation in a laser cavity, because it presents very low loss, it can be tuned easily and precisely to the comb spacing and is very simple to build. If the structure is used for such a purpose, the effective finesse of filtering may be enhanced by double pass in a linear cavity. Fig. 2(a) shows the single pass transmission function of the filter, measured using the ASE from a SOA, indicating a finesse of two. Fig. 2(b) displays the transmission of the filter in double pass configuration, showing a cos4() function and an enhanced finesse of 3.2 as expected.

Fig. 3 shows the linear cavity of the multi-wavelength source formed between two dielectrically coated mirrors of 99% reflectivity. Gain was provided from a commercially available SOA. It is a 500 μm, bulk InGaAsP/InP ridge waveguide device, with facets angled at 10° and antireflection coated. The device has a small signal gain of 23 dB at 1535 nm when driven with 250 mA dc current. The SOA exhibited a 2 dB small signal gain polarization dependence between its TE and TM axes and polarization controllers were used on its ports for polarization control. Output from the source was obtained with a 5:95 fused fiber coupler and the longitudinal cavity mode spacing was 4.4 MHz.

The wavelength comb generating filter consisted of 5.77 m of PM fiber, followed on its left side by a polarizer and a mirror. It was found that the polarization gain dependence of the SOA in conjunction with the polarization controllers, could be used to achieve the comb generating function of the filter. However the use of a second polarizing element before the right side

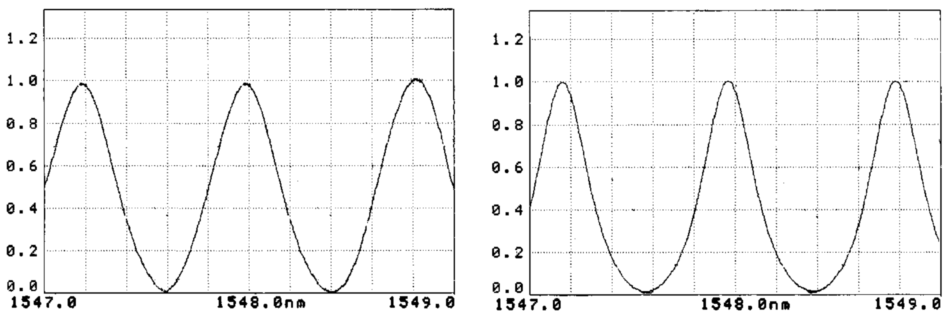

Fig. 2. (a) Single and (b) double pass transmission through the comb-generating filter.

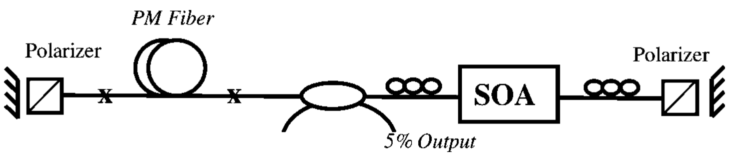

Fig. 3. Experimental layout of multi-wavelength laser.

mirror, could enhance the extinction in the troughs of the generated multi-wavelength signal by as much as 5 dB.

3. Results and discussion

With the polarization controllers and the right side polarizer adjusted to couple the oscillating signal in the high gain axis of the SOA and at 45° to the axes of the PM fiber, the source displays multi-wavelength oscillation when the SOA is driven at maximum current. Fig. 4 displays the optical spectrum and shows that 23 of the oscillating lines have less than 3 dB power variation between them. The FWHM of each oscillating wavelength was measured with an optical spectrum analyzer and was found to be 0.16 nm, close to the resolution of the instrument. In order to improve on the accuracy, the lines were also measured with an external, high finesse fiber Fabry–Perot (FFP) and were found to have 12.5 GHz FWHM. Moreover, using the 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. Fig. 5 displays the power distribution against wavelength for two of the oscillating lines and which has been fitted with a Lorentzian profile. From Fig. 5, it can be seen that the extinction ratio of the lines is about 17 dB. However, it is expected to be higher because the measurements were made after signal amplification in a bulk, 1500 μm long SOA. Theoretically, the extinction ratio of the PM based comb generating filter is significantly higher because of its cosine-squared transmission function. In order to improve on the extinction ratio the cavity loss must be decreased in order the oscillating lines to deeply saturate the SOA. The total power at the

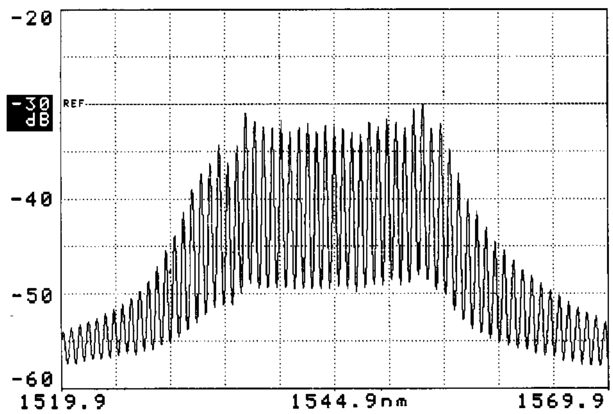

Fig. 4. Optical spectrum of the multi-wavelength laser.

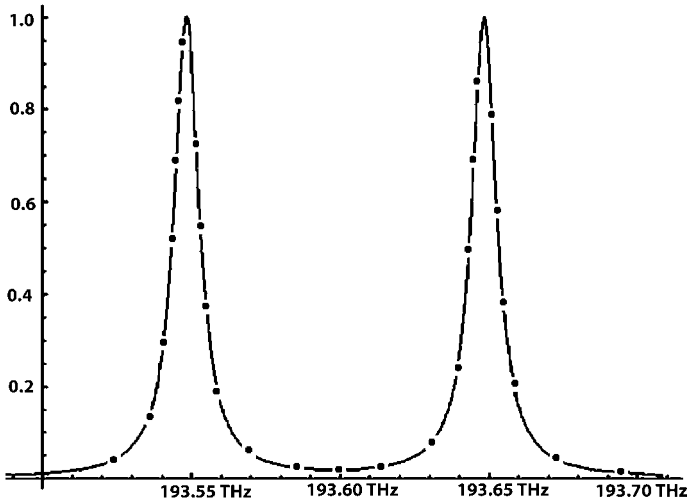

Fig. 5. Power distribution versus wavelength for two of the oscillating lines.

output of the source was 42 μW and Fig. 6 shows the power distribution across the 23 most intense lines.

The stability of the multi-wavelength laser was also tested. Due to the relatively short cavity and strong polarizing properties of the cavity the output remains stable for hours in laboratory conditions. Fig. 7 shows the 3-D temporal evolution of three lines from the output of the laser. The figure is plotted on a linear scale over a 90 min time-span and displays the good stability of the source.

It is possible to obtain simultaneous oscillation of a larger number of wavelengths, if the signal is coupled on both gain axes of the SOA. The low gain axis of the SOA (TM), causes oscillation at slightly lower wavelengths, allowing the extension of the spectrum towards shorter wavelengths. Fig. 8 shows such a condition displaying more than 30 wavelengths with less than 5 dB power variation between them. The lower gain value of the TM axis of the SOA compared to the TE, results in a systematic slant of the output

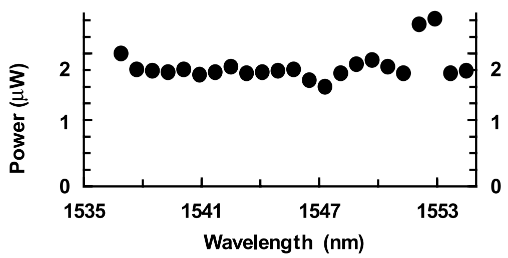

Fig. 6. Optical power variation versus wavelength.

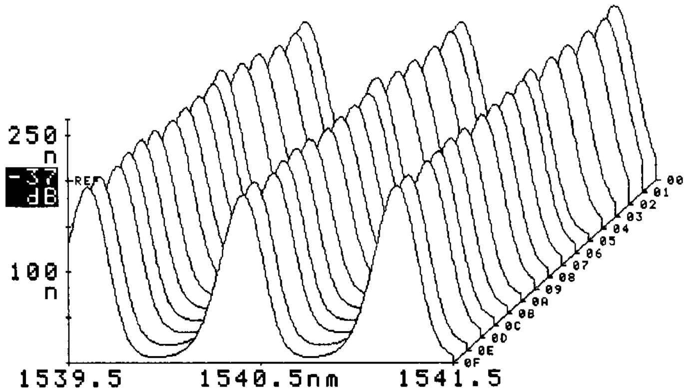

Fig. 7. Linear plot of time evolution of the output of the multi-wavelength laser over 90 min.

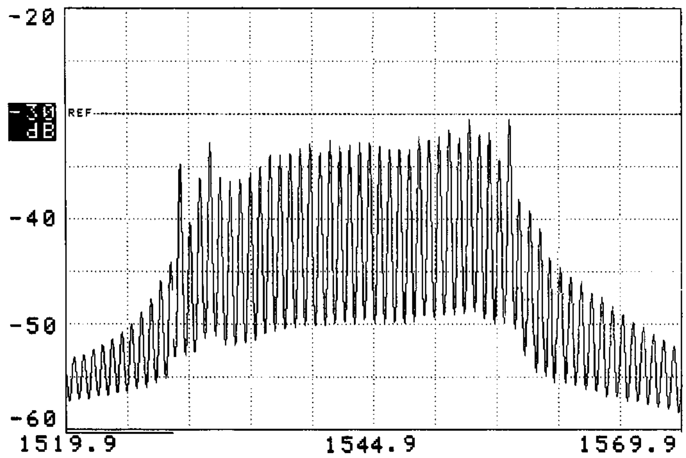

Fig. 8. Optical spectrum showing 32 oscillating wavelengths with less than 5 dB power variation.

power across these lines, which however could be removed with a filter. Also as the number of lines is increased while the drive current is kept the same, a 2 dB decrease in the extinction between the lines is observed. It is expected that using a SOA with higher gain with lower polarization gain dependence, will enhance even further the regularity, extinction and number of oscillating lines.

Mode partition noise gives rise to significant performance degradation in multi-mode, Fabry–Perot laser diodes because it results in large, time varying optical power fluctuations in each mode, even though the total power may be relatively stable. In order to determine the mode partition noise of the source, the rf noise spectrum was measured from a single wavelength and was compared to the multi-wavelength noise spectrum. If mode partition noise in the source is significant, the RIN value obtained for a single wavelength is expected to be significantly larger than for the RIN value obtained from the multi-wavelength output. In Fabry–Perot diode lasers this difference has been found to be as large as 30 dB (Ito *et al.* 1977). A single oscillating wavelength was selected using a 0.2 nm tunable optical filter, positioned at the output of the source, and was modulated using a lithium niobate modulator with less than 10% modulation depth. In the sequence, it was dispersed in 4.4 km of standard single mode fiber and was analyzed with a high speed photodiode in a 40 GHz microwave spectrum analyzer (Wentworth *et al.* 1982). At 500 MHz it was found that the effective intensity noise was −127 dB for single wavelength and −130 dB for the multi-wavelength output for 1 Hz bandwidth. The low single wavelength RIN value, which is only slightly higher than the value for the multi-wavelength output, indicates that mode partition noise from the source is low. This is a result of the fact that within the 12.5 GHz FWHM of each oscillating wavelength there are about 2800 cavity modes, so that any power fluctuations in each cavity mode within each wavelength are completely averaged out to give rise to stable operation for each wavelength. The use of a narrower optical filter for single wavelength isolation results in a deterioration of the relative intensity noise, since less cavity modes are selected. To this end, for proper line isolation and modulation, an optical filter with an effective bandwidth equal to the FWHM of the oscillating wavelength must be selected.

4. Conclusions

In summary, we have demonstrated a simple and stable multi-wavelength source. It combines a SOA and simple PM fiber filter operating as a Lyot filter. The source has been shown to be capable to oscillate at 23 wavelengths with less than 3 dB power variation across them, 17 dB extinction between them and 12.5 GHz linewidth. The source can be used in laboratory, DWDM transmission evaluation experiments and can reduce the cost of the transmitter system substantially.

Acknowledgements

K. Vlachos and Ton Koonen gratefully acknowledge partial support by the CEC via the IST program project 28557 STOLAS and G. Theophilopoulos, H. Avramopoulos via the ESPRIT program, project 36078 DO_ALL.

References

Boivin, L., M. Wegmueller, M.C. Nuss and W.H. Knox. *IEEE Photon. Technol. Lett.* **22** 446, 1999.
Collings, B.C., M.L. Mitchell, L. Boivin and W.H. Knox. *European Conference on Optical Communications*, PD1-3, 1999.
Ito, T., S. Machida, K. Nawata and T. Ikegami. *IEEE J. Quantum Electron.* **13** 574, 1977.
Lee, J.S., Y.C. Chung and D.J. DiGiovanni. *IEEE Photon. Technol. Lett.* **5** 1458, 1993.
Lewis, S.A.E., M.J. Guy, J.R. Taylor and R. Kashyap. *Electron. Lett.* **34** 1247, 1998.
Morioka, T., K. Uchiyama, S. Kawanishi, S. Suzuki and M. Saruwatari. *Electron. Lett.* **31** 1064, 1995.
Papakyriakopoulos, T., A. Stavdas, E.N. Protonotarios and H. Avramopoulos. *Electron. Lett.* **35** 717, 1999.
Park, N. and P.F. Wysocki. *IEEE Photon. Technol. Lett.* **8** 1459, 1996.
Reeve, M.H., A.R. Hunwicks, W. Zhao, S.G. Methley, L. Bickers and S. Hornung. *Electron. Lett.* **24** 389, 1988.
Shi, H., G. Alphonse, J. Connolly and P. Delfyett. *Electron. Lett.* **34** 179, 1998.
Vlachos, K., K. Zoiros, T. Houbavlis and H. Avramopoulos. *IEEE Photon. Technol. Lett.* **12** 257, 2000.
Wagner, S.S. and T.E. Chapuran. *Electron. Lett.* **26** 696, 1990.
Wentworth, R.H., G.E. Bodeep and T.E. Darcie. *IEEE/OSA J. Lightwave Technology* **10** 84, 1982.