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SOA-Based Multi-Wavelength Laser Sources

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We present recent advances in multi-wavelength, power-equalized laser sources that incorporate a semiconductor optical amplifier (SOA) and simple optical filters, such as Lyot-type and Fabry-Perot, for comb generation. Both linear and ring-cavity configurations are presented, and single-pass optical feedback technique is proposed to improve the performance in terms of the number of simultaneously oscillating lines and output channel power equalization. This technique resulted in a broadened oscillating spectrum of 52 lines spaced at 50 GHz, power-equalized within 0.3 dB. Finally, a simplified version that uses only an uncoated SOA for both gain and comb generation is demonstrated.

Keywords multi-wavelength source, comb generation, ring-cavity lasers, linear cavity lasers, Lyot filter, Fabry-Perot filter, semiconductor optical amplifiers, optical feedback

Introduction

Wavelength division multiplexing (WDM) technology is now well established, and transmission and network systems are being deployed rapidly worldwide. As the channel count continues to increase across the spectrum from S- to L-band, so has the interest in laser sources that can provide simultaneous, multi-wavelength operation. Applications for such sources include use in WDM transmitters or passive and active component characterization and may be used instead of an equivalent number of discrete laser sources or tunable laser sources to reduce cost, electronic driver real estate, or the complexity in measurement procedures. For example, multi-wavelength laser sources are ideal for the characterization of optical amplifiers where the gain profile must be saturated across its whole spectrum for reliable measurements, or polarization mode dispersion and polarization-dependent loss measurements that are usually carried out with tunable

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sources. Multi-wavelength operation has been demonstrated using a number of techniques including spectrum slicing in LEDs [1], amplified spontaneous emission from EDFAs [2], supercontinuum generation in fiber [3], femtosecond pulses [4], as well as in EDF oscillators that use an intracavity grating [5], a fiber Lyot filter [6], and a fiber grating Sagnac loop [7]. Recently, multi-wavelength operation was also shown in semiconductor optical amplifier (SOA) cavities [8–14].

This article presents a study of different implementations of multi-wavelength laser sources with power-equalized output, which use a combination of SOAs and different filtering approaches for the comb generation. We show that with a regular single SOA linear cavity that employs a polarization maintaining (PM) fiber-based Lyot-type filter it is possible to obtain simultaneous 23-line oscillation at 100 GHz nominal spacing across an 18-nm spectral window, with less than 3 dB power variation between them [14]. Improved performance is achieved in a regular ring cavity that includes two SOAs and makes use of a fiber Fabry-Perot filter (FPF) to obtain simultaneous 38-line oscillation spaced at 50 GHz across a 15-nm spectral window, with less than 0.5 dB power variation between them [11]. In order to extend the power-equalized oscillating spectrum, we further propose and demonstrate a simple technique that relies on the addition of one-pass feedback arm in the output of the source. In that way, the spectral oscillating window is broadened to 21 nm, resulting in 52 channels spaced at 50 GHz [10, 11]. In this configuration the line width is 500 MHz, the power variation across the 52 lines is less than 0.3 dB, the extinction between them is better than 32 dB, and the total power is 1.7 mW. Finally, we also propose and demonstrate a simplified version of this type of laser source that employs only an uncoated SOA in a ring cavity, in order to reduce their complexity and cost. This source is capable of generating 29 simultaneously oscillating lines spaced at 65 GHz, across a 15-nm spectral window, with less than 1.5 dB power variations.

Principle of Operation

Multi-wavelength oscillation in a laser source that uses an SOA [8–14] is possible because of its broad gain spectrum and heterogeneous spectral broadening. This can be easily achieved by incorporating an optical filter with periodic spectral transfer function in the laser cavity that acts as a comb generator. In this case, the oscillating wavelength spacing is determined by the free spectral range (FSR) of the filter. If the laser cavity employs a single SOA that has polarization gain dependence, oscillation occurs at slightly longer wavelengths for the high gain axis as opposed to its low gain axis. By coupling the signal to both gain axes it is therefore possible to extend the oscillating bandwidth, resulting in the increase of the number of discrete channels. For enhanced performance, both the transmission bandwidth around each peak resonance of the filter and the cavity losses must be kept as small as possible in order to achieve narrow line width and large extinction ratio between the channels. Moreover, the decrease of the cavity losses results in increased laser output power.

Linear Cavity Laser Using a Fiber Lyot-Type Filter

Experiment

The polarization maintaining (PM) fiber Lyot filter is a simple structure that mainly consists of a length L of PM fiber, placed between polarizers aligned at 45° with respect to the bi-refringent axes of the PM fiber, as shown in Figure 1. Due to the different propa-

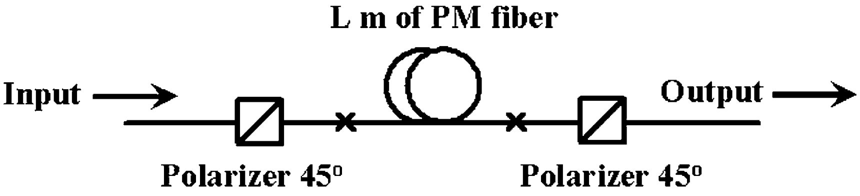

Figure 1. The Lyot-type filter.

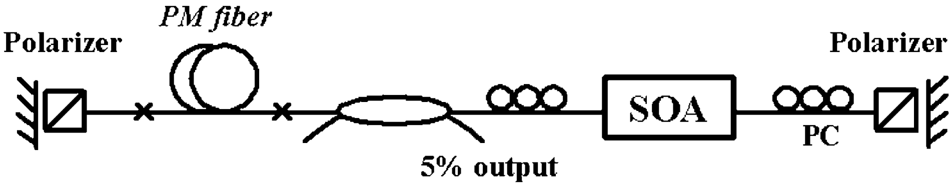

Figure 2. Experimental layout of the linear cavity laser source.

gation constants of the two axes of the bi-refringent fiber, a squared cosinusoidal filtering function is imposed on light traveling through the structure, whose FSR is determined by the length and the bi-refringence of the PM fiber [15]. The single-pass transmission function through the filter is given by:

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

where β_x and β_y are the propagation constants through the axes of the PM fiber, and 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.

In order to build a laser source capable of providing multi-wavelength oscillation, the Lyot-type filter and a gain medium have to be incorporated into the laser cavity. Such a filter is attractive for wavelength comb generation since it exhibits very low losses, it can be tuned easily and precisely to the comb spacing, and it is very simple to build. In this case, the rather low nominal finesse of the filter with a value of 2 may be effectively enhanced to a value of 3.2 by double pass in a linear cavity configuration.

Figure 2 shows the experimental setup of the multi-wavelength source, revealing a linear cavity formed between two dielectrically coated mirrors of 99% reflectivity. Gain was provided from a commercially available SOA (Opto Speed SA), which was a 500-μm, bulk InGaAsP/InP ridge waveguide, with antireflection-coated facets angled at 10°. The device has a small signal gain of 23 dB at 1535 nm and polarization gain dependence between its TE and TM axes of 2 dB when driven with 250 mA dc current. Polarization controllers were used on the output ports of the SOA to adjust the polarization of the lasing signal. The Lyot filter used in this experiment was built from 5.77 m of commercially available PM fiber with 3 mm beat length, resulting in an FSR of 100 GHz. Output from the source was obtained with a 5:95 fused fiber coupler.

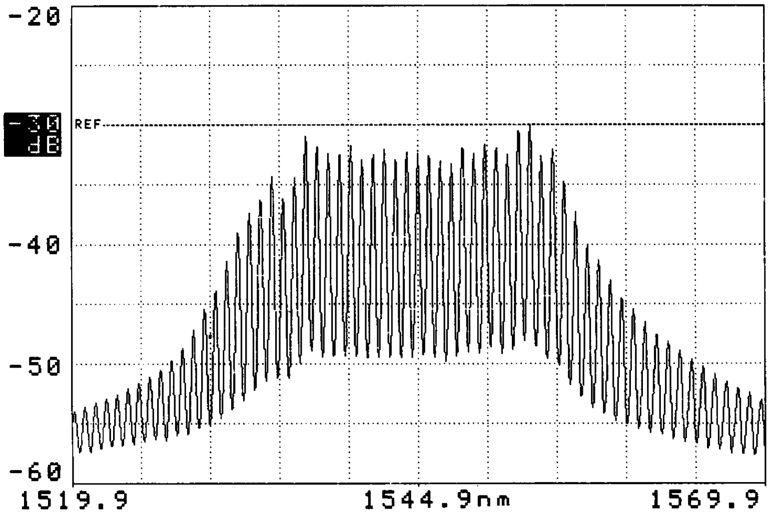

Figure 3. Optical output spectrum of the linear laser cavity.

Results

By proper adjustment of the polarization inside the cavity, the source displays multi-wavelength oscillation when the SOA is driven at maximum dc current. Figure 3 displays the optical spectrum at the output of the source and reveals simultaneous oscillation of 23 discrete channels spaced at 100 GHz with less than 3 dB power variation between them and 17 dB extinction. The FWHM of each oscillating wavelength was measured with an optical spectrum analyzer and was found to be 0.16 nm, determined by the resolution limit of the instrument. In order to improve on the accuracy of the measurement, the line width was also measured using a high finesse fiber FPF at the output and was found to be 12.5 GHz. The total output power of the multi-wavelength source was 42 μW.

Figure 4 shows additional results on the output power and the stability of the proposed laser source. More specifically, Figure 4(a) illustrates the output power distribution across the 23 most intense lines and indicates that each channel power has a mean value of 2 μW.

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. Figure 4(b) 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 minute timespan and displays the good stability of the source.

Ring-Cavity Laser Using Two SOAs and a Fabry-Perot Filter

Experiment and Results

In order to improve the performance of the multi-wavelength source in terms of the number of oscillating lines, output power, line width and extinction ratio, we have modified the laser cavity from a linear to a ring configuration and incorporated two SOAs and a fiber FPF for comb generation. The addition of a second SOA, with a peak gain slightly different from the first, increases the oscillating bandwidth and the output power, while the use of the FPF allows for free selection of the finesse. In this way, by using a higher

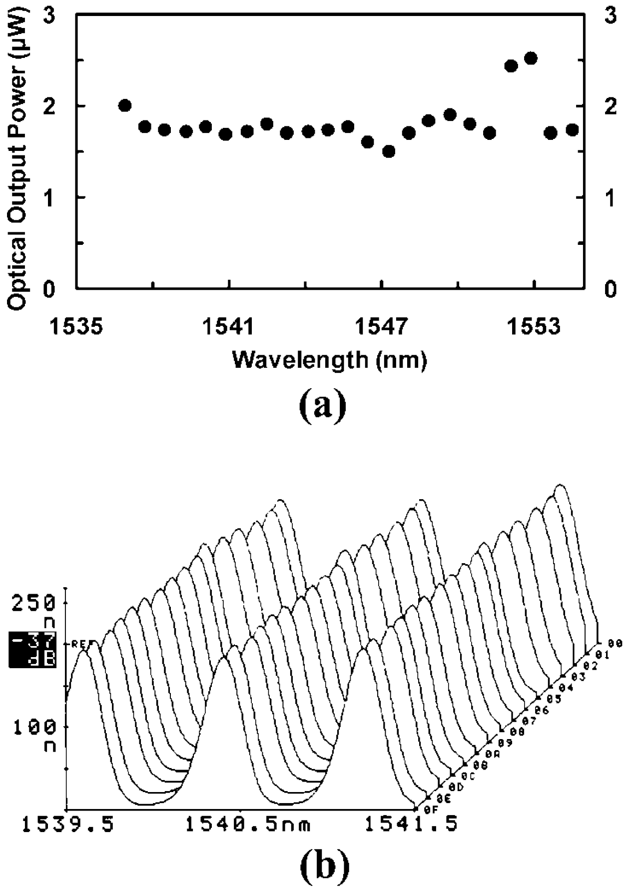

Figure 4. (a) Optical power distribution of output wavelengths and (b) output time evolution over 90 min.

finesse filter, we can effectively reduce the line width and improve the extinction ratio of the channels. It should be noted that, in the case of the Lyot-type filter, the finesse value is constant due to its cosinusoidal transfer function. Moreover, the use of the FPF imposes the design of a ring-cavity configuration that allows for unidirectional oscillation in order to avoid undesirable reflections from the etalon. Optimization of the cavity losses and adjustment of the drive currents for the two SOAs can result in a broad, uniform oscillating spectrum.

Figure 5 shows the experimental layout of the cavity that was used. Gain was provided by two bulk, 500-μm long, commercially available (Opto Speed, S.A.), InGaAsP/InP ridge waveguide SOAs, with antireflection-coated facets angled at 10°. SOA 1 provided a peak small signal gain of 22 dB at 1530 nm with 1.5 dB polarization dependence when driven with 250 mA dc current. SOA 2 provided a 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 before the SOAs to adjust the input state of polarization, and isolators were used to ensure unidirectional oscillation in the ring and to avoid undesirable reflections. The oscillating spectrum was defined by a fiber Fabry-Perot (FFP)

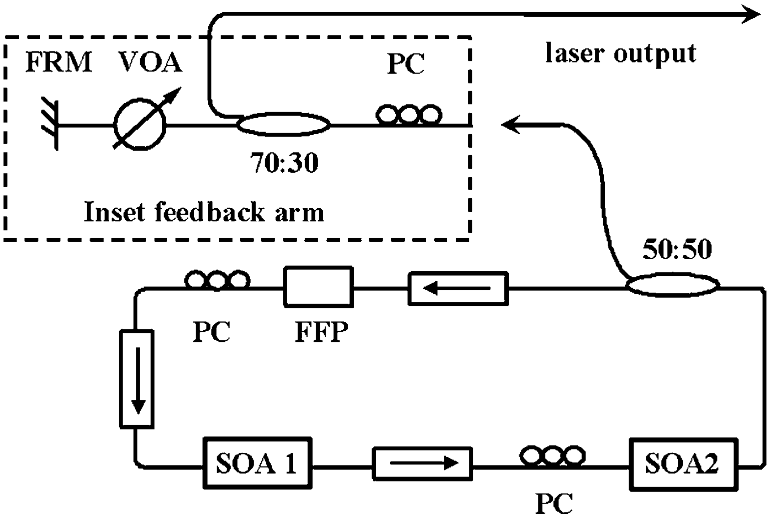

Figure 5. Experimental setup of the ring laser source and inset showing the feedback arm.

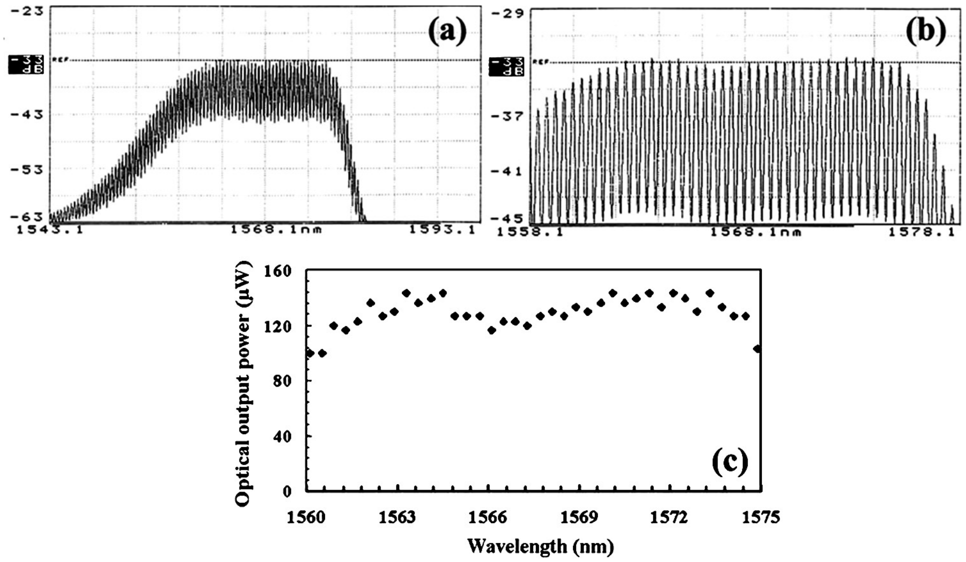

Figure 6. Optical output spectrum at (a) sweep width 5 nm/div, (b) sweep width 2 nm/div, and (c) power distribution of output wavelengths.

filter with free spectral range 47.75 GHz, finesse 8.1, and 1.7 dB insertion loss. A 50:50 fused fiber coupler provided the output from the source.

With the drive currents adjusted for SOA 1 at 207 mA (20 dB small signal gain at 1532 nm) and at 229 mA for SOA 2 (22 dB small signal gain at 1524 nm), the source oscillates across a broad spectral range shown in Figure 6(a) and (b). The 38 central lines span across 15 nm and provide nearly equal power with a mean of 127 æW and less than 0.5 dB standard deviation, shown in Figure 6(c). The total output power from the source was 5.5 mW. The line width of the oscillating lines was below the 0.16 nm resolution limit of our optical spectrum analyzer and for this reason it was deduced by measuring the beat spectrum of the cavity modes on an RF spectrum analyzer. Assuming a Lorentzian line shape, the line width was found to be 500 MHz. The extinction between the lines was measured after amplification in an EDFA using a second fiber Fabry-Perot filter (5.2 GHz bandwidth) and was found to be 32 dB. It is expected that the extinction obtained directly from the source will be significantly better than this value.

It is worth noting that multi-wavelength operation may be obtained with a single SOA, too. For example, if only SOA 2 is used in the cavity, a flat oscillating spectrum of 10 nm is obtained with 25 simultaneously oscillating lines.

Source with Single-Pass Feedback

In order to extend the power-equalized oscillating spectrum, single-pass optical feedback was employed with the setup shown in the inset of Figure 5. With this arrangement part of the output signal obtained through the 50:50 coupler is returned back to the laser via a Faraday rotator mirror (FRM) and a 70:30 coupler, while a variable optical attenuator (VOA) is used to adjust its optical power into the oscillator. The feedback signal travels in the backward direction through SOA 2 only once and is stopped by the isolators.

The oscillating signal experiences more losses in traveling from SOA 2 to SOA 1 than from SOA 1 to SOA 2 and to obtain a wide oscillating spectrum SOA 1 must be driven at a lower current than SOA 2. SOA 2 is deeply saturated, and without feedback the oscillating spectral profile is strongly featured, especially when attempting to couple to both TE and TM axes in order to broaden the spectrum. If an appropriate level of this featured spectral profile is used as saturating signal in the opposite direction to the lasing signal, equalization of the power of the oscillating wavelengths can be achieved. Essentially, the more intense lines saturate the SOA more, causing a uniform distribution of the gain across wavelength. Optimization of the cavity losses, the power of the feedback signal, the currents driving the SOAs, and the polarization controllers in the cavity results in a broad and equalized spectrum. Use of the FRM is beneficial because it ensures that the feedback signal is orthogonal to the oscillating signal and simplifies the polarization adjustments.

Figure 7 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 7(a) displays the output in the absence of the feedback and shows a broad, but highly featured, profile. With the injection of 235 μW of signal into SOA 2 from the feedback arm, the power spectrum equalizes and broadens to nearly 21 nm so that it consists of 52 oscillating wavelengths as seen in Figure 7(b). Figure 7(c) shows in more detail 49 of these 52 oscillating wavelengths, and Figure 7(d) shows their power distribution that has a mean of 33 μW and standard deviation of 0.3 dB. The total output power was 1.7 mW. The performance of the source does not depend critically on the current or feedback power values. For example, with current changes of up to 10 mA on either SOA, or variations in the feedback of up to 30 μW, there is no change in the number of oscillating lines, but there is a small increase to 0.6 dB in the power variation across the 52 lines. The line width was found to be 500 MHz and the extinction between the lines after amplification was better than 32 dB. These figures may be improved if a narrower Fabry-Perot filter is used. The polarization state of the oscillating lines was examined in a polarization state analyzer (Instruments Systems, model RPA 2000-125). All wavelengths showed greater than 97% degree of polarization and were nearly linearly

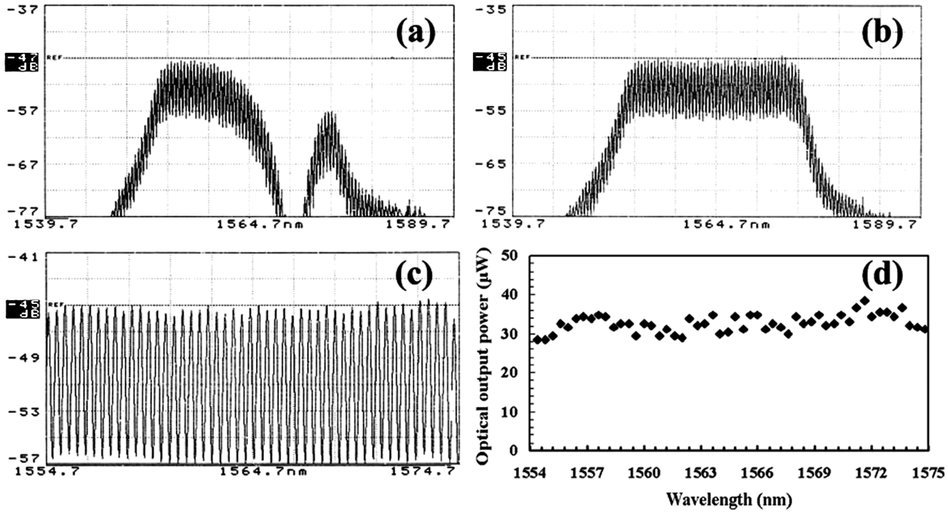

Figure 7. Optical output spectrum: (a) without and (b) with optical feedback (sweep width 5 nm/div); (c) with optical feedback (sweep width 2 nm/div), and (d) power distribution of output wavelengths with feedback.

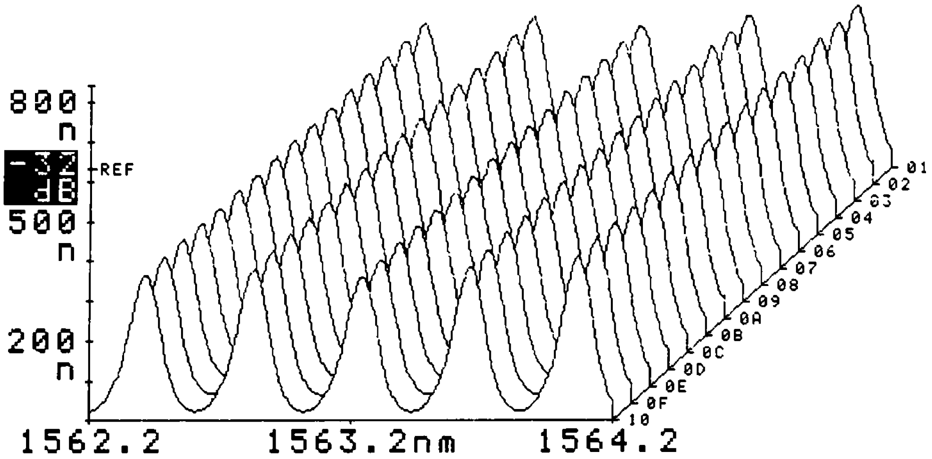

Figure 8. Output time evolution over 90 min.

polarized, even though not in the same plane. The stability of the multi-wavelength laser was also tested. Due to the relatively short cavity, the output remains stable for hours in laboratory conditions. Figure 8 shows the 3-D temporal evolution of five lines from the profile. The figure is plotted linearly, covers a 90-min time span, and displays the good stability characteristics of the source.

The feedback technique has even more pronounced effects for a cavity with a single SOA, in which case a flat oscillating spectrum of 50 simultaneously oscillating lines across 20 nm can be achieved. This should be compared to the performance of the same oscillator operating without feedback that can only sustain oscillation of flat lines across 10 nm.

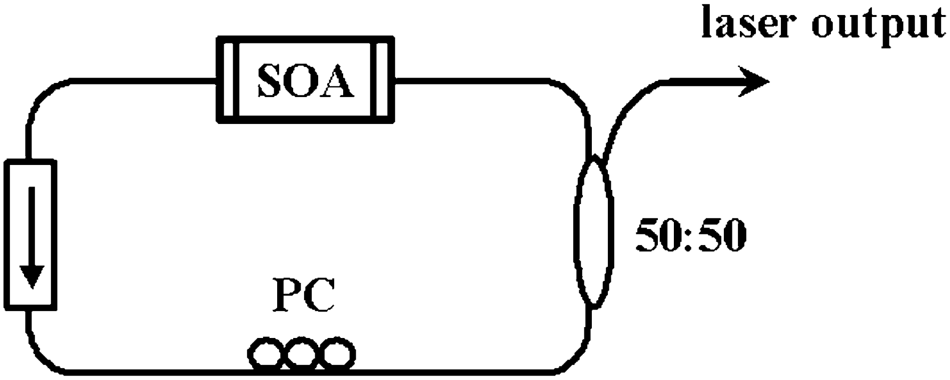

Figure 9. Experimental setup of the uncoated SOA-based ring laser source.

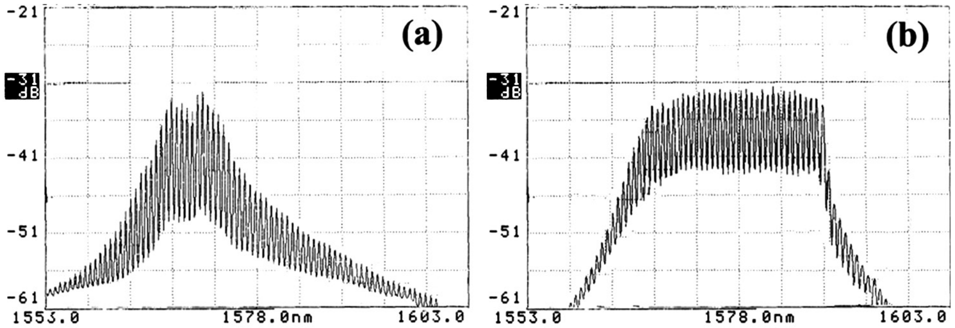

Figure 10. Oscillating optical spectrum (a) at the output of the uncoated-SOA and (b) at the output of the ring laser configuration.

Ring-Cavity Laser Using a Non-anti-reflection–Coated SOA

In order to reduce the cost and complexity of the previously described scheme, a single uncoated SOA can be used to simultaneously provide both gain and comb filtering function in the cavity. Figure 9 shows the relatively simple experimental setup used. Gain was provided by a bulk, 500 μm long, InGaAsP/InP ridge waveguide SOA (OptoSpeed, S.A.) with facets tilted at 10° and no anti-reflection (AR) coatings. The reflectance of the uncoated facets was calculated to be about 0.3. A polarization controller was incorporated to adjust polarization state and an isolator to ensure unidirectional oscillation in the ring cavity. Output was obtained via a 50:50 fused fiber coupler.

The oscillating spectrum was defined by the Fabry-Perot modes of the uncoated SOA, whose FSR was 65 GHz. Multi-wavelength operation is possible even by using the reflection-coated SOA alone considered as a linear, 500 μm long cavity, providing lasing lines determined by the Fabry-Perot modes that experience the highest gain. However, due to gain compression caused by the extreme low cavity losses, its performance as a multi-wavelength source is rather poor. Figure 10(a) depicts the oscillating spectrum of this configuration that consists of only 4 lasing lines within a 3 dB power variation when the SOA is driven at 250 mA dc current.

On the contrary, multi-wavelength operation in a ring laser configuration is significantly improved due to strong optical feedback that forces carriers to deplete the heavily saturated energy levels and occupy the less saturated, shifting the oscillating spectrum to longer wavelengths. Further bandwidth broadening is obtained by coupling the lasing signal in both polarization axes of the semiconductor. Figure 10(b) illustrates the obtained oscillating spectrum using the ring laser configuration with the SOA driven at 250 mA. The lasing window is broadened by a factor of 7 consisting of 29 oscillating lines with a power variation of less than 1.5 dB, across a spectral window of 15 nm. The total output power of the source was found to be 2 mW.

For measuring the line width and the extinction ratio of the oscillating lines, a 1.5-mm SOA and a fiber FPF with a bandwidth of 5.2 GHz were used at the output of the ring laser to amplify the output signal and to isolate each channel, respectively. In this way, the line width was again determined by measuring the beat spectrum of the cavity modes on an RF spectrum analyzer and was found to be 160 MHz, assuming a Lorentzian line shape. The extinction between the lines was found to be 29 dB, but it is expected to be significantly better if obtained directly at the output of the laser source.

Conclusion

In summary, we have presented a study for the demonstration of multi-wavelength, power-equalized laser sources that use SOAs combined with comb generating filters in different cavity configurations. We have shown that in a regular linear cavity that includes an SOA and a fiber Lyot filter it is possible to obtain simultaneous 23-line oscillation at 100 GHz nominal line spacing, with less than 3 dB power variation, whereas a ring-cavity configuration with two SOAs and a fiber FPF provided 38 channels spaced at 50 GHz and power equalized within 0.5 dB. We have further proposed and demonstrated a simple technique for extending the power-equalized oscillating spectrum that relies on single-pass feedback of the output signal into the source. With this technique it was possible to extend the oscillating window to 21 nm and allow the simultaneous oscillation of 52 lines, with 500 MHz line width, power variation of less than 0.3 dB across the oscillating lines, and better than 32 dB extinction between them. Finally, we have presented a simplified version of these sources by incorporating an uncoated SOA into a ring cavity, avoiding in that way the additional use of a comb filtering element. This source has been shown to provide 29 simultaneously oscillating wavelengths spaced at 65 GHz with power variation less than 1.5 dB. The specific source is relatively simple and, in principle, can be integrated into a PLC platform. All the sources demonstrated here remained stable for hours in laboratory conditions and may be useful for component characterization and WDM networking applications.

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Biographies

Nikos Pleros, born in 1976, obtained the Diploma of Electrical & Computer Engineering from the National Technical University of Athens (NTUA) in 2000. In December 2000 he joined the Photonics Communications Research Lab, NTUA as a Ph.D. student, and he is now in the final year of his graduate studies. His research interests include cw and mode-locked laser sources for high data-rate telecommunication applications, all-optical digital logic modules, all-optical packet/burst switching, and semiconductor-based switching devices. Mr. Pleros was one of the 12 recipients of the annual international IEEE/LEOS Graduate Student Fellowship Program for the year 2003. He was also awarded the 15th prize in the Greek Mathematical Olympiad in 1993. He has more than 20 archival journal publications and presentations including invited contributions and is a member of the IEEE/LEOS.

Thanassis Houbavlis was born in Athens, Greece, in November 1967. He received the Diploma of Physics with specialization in lasers from the University of Athens, Athens, Greece, in 1992; the M.Sc. degree in optoelectronics and laser devices from the Universities of Edinburgh and Saint Andrews, Scotland, in 1994; and the Ph.D. degree in optical communications from the Photonics Communications Research Laboratory, National Technical University of Athens, Athens, Greece, in 1999. His Ph.D. research focused on the design and implementation of ultrahigh-speed all-optical gates and subsystems. He has participated in various European and national research projects. He is the author or coauthor of several articles in international technical journals and conferences. Dr. Houbavlis is a Member of FITCE.

George Theophilopoulos (M'04) was born in Athens, Greece, in 1976. He received the Diploma of Electrical and Computer Engineering from the National Technical University of Athens (NTUA), Athens, Greece, in 1999, and the Ph.D. degree in electrical and computer engineering from the Photonics Communications Research Laboratory (PCRL), NTUA, in 2003. Since then, he has been a senior research associate in PCRL. His research interests include all-optical logic, all-optical switches, optical networks, and semiconductor switching technologies. He is the author or coauthor of 20 publications.

Dr. Kyriakos Vlachos received his Diplom-Ingenieur Degree in Electrical and Computer Engineering from the National Technical University of Athens (NTUA), Greece, in 1998, and his Ph.D. in electrical and computer engineering from NTUA in 2001. From 1997 to 2001 he has been a senior research associate in the Photonics Communications Research Laboratory. From January 2001 to June 2003 he was member of the technical staff of Bell Laboratories, Lucent Technologies, The Netherlands. He is currently a postdoctoral researcher at the Computer Networks Lab at the University of Patras. His field interest includes high-speed laser sources, all-optical logic circuits (AND/XOR gates and optical circulating shift registers), and novel label swapping schemes for optical switched networks. Dr. Vlachos has participated in various European R&D Programs (DO-ALL, STOLAS, PRO3, HARMONICS) and various national projects funded by the Greek government. He is author or coauthor of more than 30 publications.

Chris Bintjas (St.M'02) was born in Athens, Greece, on February 2, 1977. He obtained the diploma of electrical and computer engineering from the National Technical University of Athens (NTUA), Greece, in 1999, and the Ph.D. degree in electrical and computer engineering from the Photonics Communications Research Laboratory (PCRL), NTUA, in 2003. During the summer of 2000, he spent two months working at Corning, Inc., on theoretical and experimental investigation of the generated crosstalk in WDM-CATV networks. His research interests include all-optical logic, optical packet/burst switching, time-division multiplexed networks, and semiconductor switching technologies.

Prof. Hercules Avramopoulos is currently heading the Photonics Technology Research Laboratory of the National Technical University of Athens (NTUA). From 1989 to 1993 he worked as a member of technical staff in the Digital Optics Research Department of AT&T Bell Laboratories, Holmdel, New Jersey. His primary research interests have centered on the demonstration of novel concepts in photonic technologies for telecommunications. For the past 10 years he has worked on, and more recently supervised work on, ultrahigh-speed, bit-wise, all-optical, logic circuits, and he has been interested in demonstrating their feasibility as a commercially viable technology for the telecommunications industry. Prof. Avramopoulos has been awarded four international patents in ultrahigh-speed switching systems and has more than 100 archival journal publications and presentations.