40nm wavelength tunable gain-switched optical comb source

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Abstract: A wavelength tunable optical comb is generated based on the gain-switching of an externally seeded Fabry-Pérot laser diode. The comb consists of about eight clearly resolved 10GHz coherent sidebands within 3dB spectral envelope peak and is tunable over the entire C-band (1530 to 1570nm). The optical linewidth of the individual comb tones is measured to be lower than 100kHz, and the RIN of the individually filtered comb tones (<-120dB/Hz) is shown to be comparable to the entire unfiltered comb (<-135dB/Hz). Besides, expansion of the tunable gain switched comb is achieved with the aid of an optical phase modulator, resulting in near doubling of the number of comb tones.

OCIS codes: (140.3520) Lasers, injection-locked; (250.4110) Modulators.

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1. Introduction

Long haul optical transmission systems are beginning to experience a "capacity crunch" due to the filling up of the portion of the spectrum that can be amplified optically [1, 2]. For this reason, a strong trend in recent years is towards the use of advanced optical modulation formats which offer improved spectral efficiency compared to legacy On-Off Keyed (OOK) formats [3, 4]. To date, the minimum spacing of channels in Dense Wavelength Division Multiplexed (DWDM) systems has been 50GHz and using these advanced modulation formats, data rates of up to 100Gb/s can operate in this 50GHz grid. Further improvements in spectral efficiency will require tighter packing of channels, and a suitable technique for doing so is Orthogonal Frequency Division Multiplexing (OFDM) [5–8]. By using orthogonal frequencies, data channels can be overlapped without interference, which allows even greater spectral efficiencies to be achieved. A key component in the transponders of these OFDM systems will be an optical comb source [9, 10]. In order to be successfully employed in such OFDM systems, these optical frequency comb sources have to demonstrate good spectral flatness, stability, low linewidth and wavelength flexibility. One of the conventional approaches used in realizing a comb source is based on mode-locked semiconductor lasers (MLLs) [9]. Although this technique can generate multi-carrier signals spanning over a wide bandwidth, it inherently suffers from cavity complexity and does not offer the free spectral range (FSR) tunability since the comb line spacing is fixed by the cavity length of the laser. Moreover, the optical linewidth of the individual comb lines can be relatively large (several MHz) preventing higher order (or low baud rate) advanced modulation formats to be imposed. More recently wavelength tunable comb generation by use of external optical modulators has been reported where the line spacing and the central wavelength of the comb can both be varied. This could involve single [11] or multiple external modulators with cascaded [12], nested [13] or loop structures [14]. However, the large insertion loss of the modulator (especially when cascaded) coupled with the modulation efficiency can prove prohibitive. Another technique employed entails the use of phase modulation in an amplified fiber loop with the main disadvantages being poor spectral flatness and the limited optical linewidth of the laser source in order to suppress Brillouin induced instabilities in the comb spectra [15].

Previously, we reported on the gain switching [16] of a Discrete Mode (DM) laser diode as a means of generating highly coherent picosecond pulses at 10.7 GHz and also compared the gain switching performance of DM lasers with that of conventional Distributed Feed-Back (DFB) laser diodes [17]. This technique was used to illustrate that the high SMSR, low jitter pulses with a corresponding frequency comb spectral output could allow the gain switched DM laser to be used as a frequency comb generator. Such a comb generator enables simple and cost efficient generation of lightwaves with the precisely controlled channel spacing required for high information spectral density communication systems. However, the generated optical comb was not wavelength tunable since the discrete mode lasers were fixed in wavelength. Tunability of the comb source will enable a single component to operate on any specific wavelength channel, greatly reducing network operating costs through sparing and inventory savings.

In this paper, we propose a novel approach that makes the gain-switched comb source more flexible for future optical communication networks. We demonstrate a potentially cost-

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effective wavelength tunable optical comb source based on the gain-switching of an externally injected Fabry-Pérot (FP) laser diode (LD). In this manner, a highly coherent multi-carrier signal consisting of about eight clearly resolved 10GHz tones generated within 3dB of the spectral envelope peak with an extinction ratio in excess of 50dB can be achieved, and the generated optical comb is tunable over a wavelength range of 40nm (1530nm to 1570nm). Moreover, with the aid of a narrow linewidth External Cavity Laser (ECL-master) injecting the FP laser (slave), we show it is possible to transfer the low linewidth of the master to the individual comb tones. The optical linewidth of the individual tones across the whole tunable span is measured to be lower than 100kHz, which clearly highlights its merit for use in systems employing multi-level advanced modulation formats. In order to enhance the commercial applications and viability of this wavelength tunable comb source, we also carry out spectral comb expansion by employing a Phase Modulator (PM). This results in the doubling of the number of phase locked optical carriers within a 3dB spectral window.

2. Experimental setup

The schematic configuration of our tunable optical comb source is depicted in Fig. 1 consisting of an optical part (continuous lines) and an RF part (dashed lines). The FP LD (slave) laser used in our experiment is a 200µm long device in a high speed butterfly package. The threshold current of the laser is around 8mA at room temperature, and the device emits in the 1.5µm window. The small signal modulation bandwidth was measured at room temperature to be around 11 GHz when biased at 40 mA ($5I_{th}$). A tunable External Cavity Laser (ECL) acting as a master injects light into the slave laser, via a circulator, which enables the seeding of 20 longitudinal modes of the FP LD thereby achieving single mode operation at these selected wavelengths. The wavelength of the master is tuned to match one of the longitudinal modes of the slave and the injected power incident on the slave laser diode varies from about −15 to −20 dBm after taking into account the losses incurred in the optical injection path. The slight variation in the injected powers is due to the fact that, higher injection powers are required to achieve optimum single mode operation around the edges of the FP laser gain curve. A polarization controller (PC 1) is used to align the polarization state of the injected light with the optical waveguide of the slave laser.

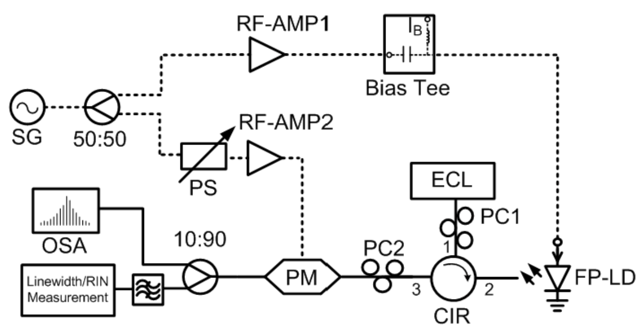

Fig. 1. Experimental setup for the tunable comb generation scheme using an externally injected, gain-switched FP-LD for comb generation, and phase modulation for comb expansion.

The externally injected slave laser is then gain-switched with aid of a 24dBm RF sinusoidal signal in combination with a 40mA dc bias applied via a bias tee. The resulting optical comb is then put through a 10Gb/s Phase Modulator (PM) for further expansion and shaping of the comb tones. A second polarization controller (PC 2) is placed at the input of the phase modulator to optimize the state of input polarization. The insertion loss of the PM is about 3dB over the entire C band. The modulation level of the driving signal to the PM is around 18 V, which corresponds to about $4V_\pi$ (V_π ~4.5V at 10GHz). The PM is driven by an amplified sinusoidal waveform drawn from the same signal generator used for gain-switching. An RF Phase Shifter (PS) is used to optimize the phase of the applied modulation signal. An

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optical coupler (90:10) is placed after the PM, with 10% of the signal being used to record the generated optical frequency comb with the aid of an Optical Spectrum Analyzer (OSA) that has a 20 MHz resolution and 90% of the signal being sent to linewidth and Relative Intensity Noise (RIN) measurement schemes.

3. Results and discussions

The free-running spectrum of the FP LD is shown in Fig. 2(a), under a bias current of 40mA. The longitudinal mode spacing of the FP LD is approximately 2nm which corresponds to the laser cavity length of 200µm. By carefully adjusting the polarization state of the injected signal from ECL, precise injection into a particular FP mode results in single mode operation of the FP-LD. An example of the single mode injection-locked operation at 1551nm with a side-mode-suppression-ratio (SMSR) greater than 60dB is illustrated in Fig. 2(b). With the fine tuning of ECL injection over a wide wavelength range, over 20 single mode operation points can be realized with high SMSR. It is also important to note that the FP laser gain curve can be shifted in wavelength by about ± 1nm by temperature tuning, which can be used to ensure that the chosen longitudinal mode is aligned in wavelength with the ITU grid.

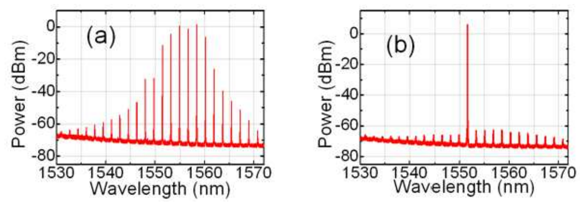

Fig. 2. Optical spectra (a) free running FP-LD @ 40mA bias and (b) externally injected FP-LD.

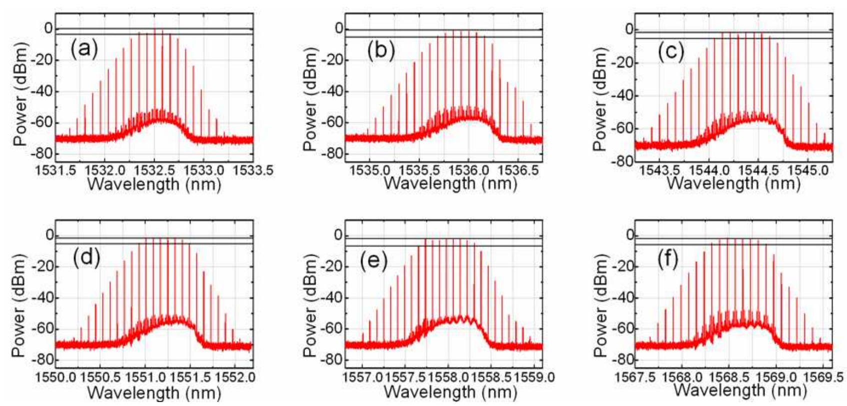

Fig. 3. Optical spectra of external injection seeded, gain-switched optical combs at different operating points (a)-(f) Wavelength tuning range from 1530nm to 1570nm (40nm)

Gain-switching at these operating points results in the generation of highly coherent frequency combs at each FP laser mode from 1530nm to 1570nm, and these combs consist of 5~8 clearly resolved 10GHz tones generated within 3dB of the spectral envelope peak with an extinction ratio of around 50dB, as shown in Fig. 3(a)-(f). Note that the relatively small number of comb lines (~5 lines) between 1530nm-1540nm in Fig. 3(a) and (b) is due to the gain profile of the FP LD under certain bias and temperature conditions (Fig. 2(a)), and these conditions are kept unchanged for all operating points.

Subsequently, the expansion of this comb when passed through the phase modulator for some of the above mentioned operating points is presented in Fig. 4(a)-(c). The phase modulation proves to be an effective means of improving the comb line number and comb flatness, as in the Fig. 4(c) where 16 lines in a 3dB spectral window has been achieved at 1568nm and very similar results are obtained around 1530nm-1540nm in Fig. 4(a)-(b). The

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spectra are taken by tuning the phase shifter only and all other conditions unchanged. Therefore even with the unbalanced gain curve of the FP-LD nicely flattened combs can be obtained over the entire wavelength tuning range.

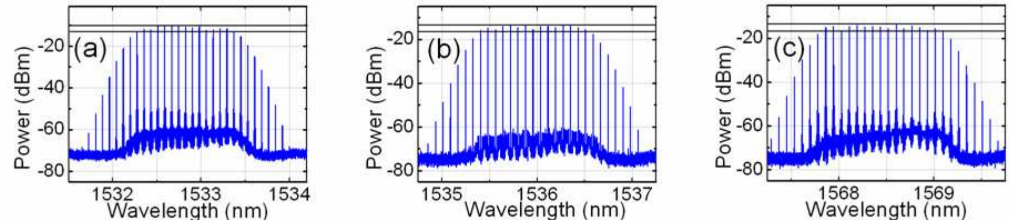

Fig. 4. (a)-(c) Optical combs consisting of 14~16 tones which are expanded via phase modulation.

After the comb expansion, the signal is sent to a tunable optical band-pass filter and subsequently into a linewidth and relative intensity noise (RIN) measurement set-ups. The tunable optical band-pass filter, with a 3dB bandwidth of 10GHz, is used to select out individual comb lines from each of the operating points to enable the linewidth measurement of the tones of the comb. The linewidth measurement is enabled with a delayed self-heterodyne scheme [18]. 14 of the operating modes, within the wavelength tuning range, are chosen and at each of these operating modes, 3 individual comb tones are filtered and measured. The individual comb line optical linewidth is measured to be lower than 100kHz. The linewidth of the master (ECL) is also measured, for comparison, and recorded as ~100kHz over the C band. (See Fig. 5.)This clearly illustrates that the optical linewidth of the individual comb lines follow the linewidth of the master laser [19].

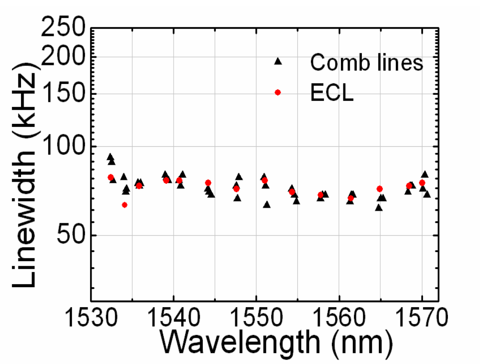

Fig. 5. Optical linewidth of the selected comb lines (black triangle) and the external cavity laser (red circles) at the operating points over the 40nm wavelength range.

The narrow linewidth of the comb represents superior phase noise characteristics thereby making such comb source a suitable transmitter for systems utilizing advanced modulation formats. The measured linewidth should make these optical comb lines suitable for use in coherent systems operating at baud rates of 10 Gbaud/s with 32-QAM.

RIN measurements [20] are carried out at 3 of the operating wavelengths (1530nm, 1550nm and 1570nm). Two different scenarios are verified at each of these operating wavelengths: (1) RIN of unfiltered comb at the given operating wavelength, and (2) RIN of a 3 individually filtered comb lines at each of the operating wavelength as “line 1” “line 2” and “line 3”. The achieved results are shown in Fig. 6. The averaged RIN (DC to 10GHz) for the entire optical comb at the 3 operating wavelength is around −135dB/Hz whereas the averaged RIN is below −120dB/Hz for all the 9 individually filtered comb lines. This clearly shows that the RIN of the individually filtered comb tones is not much higher than the entire comb indicating that the effect of mode partition noise is minimal unlike in quantum dash mode locked lasers [21].

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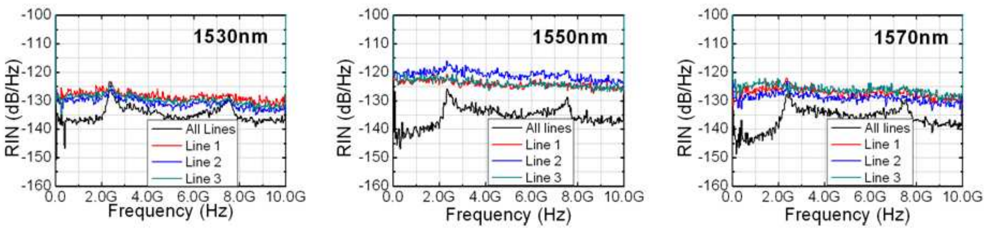

Fig. 6. RIN measurement of the 3 chosen operating modes and of the individually filtered comb lines.

4. Conclusion

In conclusion we demonstrate a wavelength tunable coherent optical comb generation scheme with a gain-switched and externally seeded FP laser. The scheme is simple, potentially cost-effective, and a flat optical comb with 5-8 comb lines within 3 dB flatness criterion is achieved with a wavelength tunability of 40nm. We also use a phase modulator to broaden the gain-switched comb. The number of comb lines is doubled after going through the comb expansion scheme. The narrow linewidth of the individual comb lines (<100kHz) enhances the potency of such a comb source in many coherent applications. The RIN of the comb lines is also measured and turns out to be below −120dB/Hz at the selected operating wavelengths. In summary, such a comb generator enabling simple and cost efficient generation of lightwaves with precisely controlled channel spacing and narrow linewidth will be an asset for achieving high information spectral density communication systems especially in systems targeting Terabit per second applications and beyond. Besides, the cost-effectiveness of the tunable comb generator can be further improved by replacing the injection master laser with an integrated electronically tunable laser.

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