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All-optical synchronization of a 40 GHz self-pulsating distributed Bragg reflector laser to return-to-zero 10, 20 and 40 Gbit/s data streams

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ABSTRACT

This paper presents experimental investigations of the all-optical synchronization of a distributed Bragg reflector (DBR) laser self-pulsating at 40 GHz on various injected bit-rate signals. Even though there is no modulation applied to this laser, it exhibits a modulation of its output emission, measured at 39.7 GHz with a linewidth of 30 MHz. Such performance is exploited in all-optical clock recovery for a return-to-zero data stream at 40 Gbit/s. The SP-DBR laser wavelength and the injected signal wavelength are 10 nm apart. All-optical synchronization is demonstrated at 40 Gbit/s with a linewidth of less than 20 MHz for injected signals at 10 and 20 Gbit/s, respectively. Thus the SP-DBR laser proves to be very versatile and can be synchronized on various bit-rate data signals.

1. Introduction

In order to improve transmission distance, transparency, capacity and speed of optical networks, the optoelectronics research industry is investigating practical means for all-optical treatment of the data [1–3]. All-optical clock recovery regeneration at 40 Gbit/s and beyond appears to be a crucial element for future transparent networks. One solution to achieve the regeneration is an all-optical clock recovery element combined with a Mach–Zehnder interferometer. In this respect truly all-optical clock recovery is of very high interest as it would supersede the current complicated optoelectronic schemes including: a high speed photo-receiver, a high-Q filter, a power amplifier and a high speed laser or an integrated laser modulator. Among the different approaches investigated so far, we mention only the most relevant ones.

The potentially simplest way to recover the clock signal from a data stream is to isolate the carrier frequency and the sideband components from the incoming data spectrum. This can be achieved by using a Fabry–Perot (FP) resonator [4]. The quality of the recovered clock signal is highly dependent on the bandwidth of the resonator. In order to achieve a required 40 MHz linewidth for clock signal at a rate of 40 Gbit/s, a finesse of 1000 is needed, which cannot be achieved easily in integrated optics. The stimulated Brillouin effect is another approach [5]. This technique exploits the narrow bandwidth (~40 MHz at 1550 nm) of the gain generated from this non-linear effect in silica fibre. The advantage of this technique is to be able to retrieve simultaneously the clock signal from one or more channels. Unfortunately, this technique requires a very high input power (~18 dB m) and its performance is too polarization sensitive. Fibre ring lasers can be used for clock recovery as well. These lasers are mode-locked to a repetition rate equal to the data rate or to a sub-harmonic of it [6,7]. The modulation is achieved passively by implantation of a Kerr element in the fiber ring or actively by modulating either the saturable absorber section or the gain section of the DBR laser. The drawback of this technique is that the high modulation speed scheme required leads to an expensive cost.

The major drawback of the three techniques briefly detailed above is that the recovered clock signal is at same wavelength or quite close to the one of the data signal. In terms of telecommunication this restricts the range of applications and makes the recovered clock signal difficult to be discerned from the data signal.

Solutions allowing a recovered clock signal at another wavelength are more attractive in this respect: The injection-locking of a FP laser is one alternative [8]. Two modes of a FP laser are injection-locked to a carrier and the clock side-peaks of an incoming data signal. The phase correlation between the carrier and the side-band modulation is transferred to the FP laser spectrum. This technique requires a pre-equalization set-up since in a return-to-zero (RZ) format the power confined at the carrier frequency is larger than that in the side-bands. Consequently, the complexity of this configuration is drastically increased.

Self-pulsating (SP) lasers are a very attractive solution. Self-pulsation is a periodic variation of the output power even though the laser is DC biased. SP lasers have many applications: in data storage for example since they have a short coherence length and low sensitivity to feedback; in terahertz generation due to their

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compactness and their ability to work at room temperature [9,10], in optical telecommunications,due to the fact that the self-pulsation phenomenon synchronizes its frequency to the bit-rate of an incoming RZ data signal [11]. There are two types of SP lasers that are attractive for clock recovery application, the distributed feedback (DFB) laser and the distributed Bragg reflector (DBR) laser. They both are compact and require a small amount of power to be locked to the data rate. The first type can involve several configurations of DFB lasers. One of them is a DFB laser coupled to an active mirror. The SP is due to the instability resulting in the Bragg mirror reflectivity during the lasing regime. This leads to a dispersive self-Q-switching [12]. The SP frequency achieved is below 40 GHz. In order to achieve speeds, a new structure has been imagined. The gain-coupled DFB laser is composed of two sub DFB sections merged to a phase section [13,14]. Both sub-sections have a specific corrugation step and thus are spectrally detuned. The self-pulsation originates from the beating between these two longitudinal modes coexisting in the cavity. The main drawback of these components is the complexity of their structure, which ultimately impacts their production cost. The other option is the distributed Bragg reflector (DBR) laser. It presents the advantages of low polarization dependence, a low power consumption, a reduced foot-print and it can be mass-produced at a reduced cost. In this structure, under certain bias conditions, the beating between the longitudinal modes generates a power oscillation. The non-linearities and characteristic times of semiconductor devices lead to an oscillation in the radio-frequency (RF) domain. It has been demonstrated that the SP-DBR laser is able to synchronize its self-pulsation to the bit-rate of an incoming data signal, acting as an all-optical clock recovery device [15]. The process of clock recovery is performed by the synchronisation of one of the tones of the SP-DBR laser to one of the tones of the bit-rate of the data stream. One of the main advantage of the scheme is that the data signal is kept in optical format. The response of the SP-DBR laser is kept in the optical format; therefore there is no need for optical/electrical conversion. Another advantage is that, since the retrieved signal of the SP-DBR laser is at another wavelength, both data stream and SP-DBR output can be coupled into a non-linear device, such as a SOA for all-optical processing. For instance, the synchronised signal from the SP-DBR can be interfaced to an optical reamplification, reshaping and retiming (O3R) function [16].

The aim of this paper is to investigate its potential for synchronization of its intrinsic modulation at 39.7 GHz to various data rates from 10 to 40 Gbit/s. We demonstrate the potential of the device for synchronisation at low bit-rate, and we compare the SP-DBR laser's performances at 10, 20 Gbit/s to that at 40 Gbit/s. The assessment of this device's performances has also been carried out in the spectral domain and temporal domain using a FROG technique.

From 10 to 20 Gbit/s the harmonics frequency of the clock signal synchronizes the fundamental frequency of SP-DBR laser. At 40 Gbit/s the fundamental frequency of the clock synchronizes the fundamental function of the SP-DBR laser. These performances open up a large range of all-optical applications i.e. clock extraction or optical sampling which could be beneficial in the development of future all-optical functions.

The paper is organized as follows: In Part I details on the laser structure and its performances as RF oscillator are given, in Part II we introduce the experimental set-up and in Part III some results on synchronization at 10, 20, 40 Gbit/s characterized in the frequency and time domains are presented.

2. Laser description, characterisation and features

As shown in Fig. 1, the SP-DBR laser is a 3-section component. Each of the sections is electrically isolated from the other one by more than 3 kΩ. The bulk gain section is 790 μm long and is made of bulk quaternary active material. Its quasi-square transverse dimensions, 0.4 μm × 0.6 μm for thickness and width, respectively, ensure a low polarization-sensitivity of modal gain [17] and a special single mode behavior of the electric field. The phase section is 130 μm long, with a waveguide width expanding linearly up to the 1.8 μm width of the Bragg section.

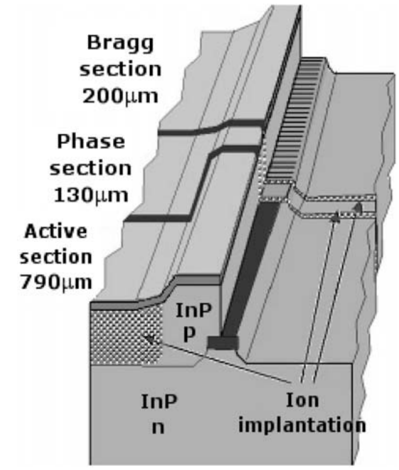

Fig. 1. Schematic of the SP-DBR laser.

The short 200 μm long Bragg section enables us to have at least two longitudinal modes inside the 3 dB linewidth of the Bragg reflection spectrum. As a result, the DBR laser operates in either a multimode or a single mode regime depending on the bias condition. The extinction ratio of the output oscillation can be enhanced by adding to the described structure a saturable absorber section (not represented in Fig. 1). It must be mentioned that the criterion for self-pulsation is not related to the presence of a saturable absorber section in the laser cavity. For instance, in [18] we studied a DFB laser with no saturable absorber and this device was not mode-locked, but presented self-pulsation.

The current in the gain section is labeled I_g, in the Bragg section I_B. The values of these currents will control the number of modes of the optical spectra and the amplitude/phase of each mode. The current in the phase section will be always set at 0 mA and will not be mentioned in the rest of the paper.

Fig. 2 shows a typical light current in the gain section characteristic of a SP-DBR laser. The device is temperature controlled at 297 K. The light output was collected by 0.4 NA GRIN lens and recorded on a slow response power-meter as a function of the increasing and decreasing current of the gain section for a DBR and phase sections left unbiased. The threshold current is 30 mA. There is no hysteresis loop observed in the LI curve, confirming the absence of saturable absorber section.

With active and Bragg sections biased at $I_g = 181.83$ mA and $I_B = 1.75$ mA, respectively, the optical spectrum was recorded using a high resolution optical spectrum analyzer with a 80 fm resolution as depicted on Fig. 3. The longitudinal spectrum features three modes separated by 0.3 nm, which corresponds to a 39.7 GHz free spectral range at 1557 nm. The resolved linewidth is 224.57 MHz, 74.133 MHz and 81.521 MHz, for the mode 1, 2 and 3, respectively. The side-mode-suppression ratio is approximately 17 dB, confirming that the device is multimode.

The optical output is launched into 50 GHz bandwidth photodiode connected to a 40 GHz electrical spectrum analyzer (ESA). No direct or external modulations are applied to this device. The SP-DBR laser is biased at 181.49 mA and 1.75 mA for I_g and I_B, respectively. The electrical spectrum is recorded with a resolution of 3 MHz and a video bandwidth of 3 kHz and is shown on inset of

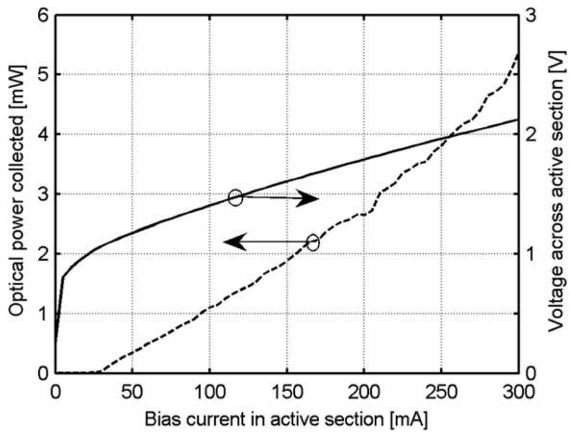

Fig. 2. Collected light output and voltage across the gain section as a function of I_g with $I_B = 0$ and for phase section set at 0 mA.

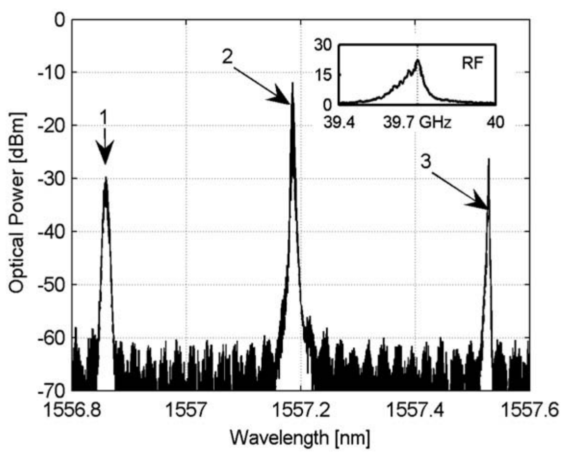

Fig. 3. High resolution optical spectra produced by SP-DBR device with no externally injected signal, biased at $I_B = 1.75$ mA and $I_g = 181.49$ mA and temperature controlled set at $T = 297$ K. On inset RF spectra measured under the same bias and temperature conditions.

Fig. 3. The RF signal is centered at 39.7 GHz, corresponding to the free spectral range of the three modes, and its full width at half-maximum is 30.19 MHz.

It is found that the sum of the linewidth of each mode is larger than that of the RF signal. The RF linewidth benefits from a phase correlation between the lasing modes through the non-linear intra-cavity effects. Indeed, the four-wave-mixing (FWM) results in a modulation of the carrier population, leading to a nonlinear gain and refractive index modulation, affecting both the amplitude and the phase of the lasing modes. The phases of each mode are correlated to each other, resulting in a reduction of the phase noise, and thus the RF signal linewidth [19]. The self-pulsation in this device can be understood as a passive mode-locking.

The following criterion: (1) can be used to identify the self-pulsation phenomenon:

$$\Delta\nu_{RF} \ll \sum_i \Delta\nu_i$$

where $\Delta\nu_{\mathrm{RF}}$ is the linewidth at the RF frequency and $\Delta\nu_i$ the linewidth of the ith optical mode. This criterion occured after a series of measurements which assessed the origin of the SP in our device. The experimental and theoretical work in [19] have demonstrated that the quenching of the linewidth reveals the passive mode-locking in the multimode laser. A RF signal of less than 40 MHz is achieved with this device. As the SP-DBR laser has a measured finesse of more than 1000, it is of great interest to assess its performance for all-optical clock recovery and synchronization.

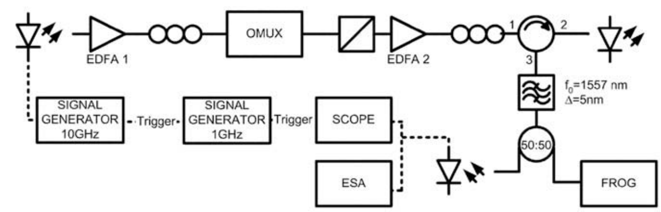

Fig. 4. Experimental set-up of optical synchronization of the SP-DBR laser. Full lines correspond to single mode optical fibre, the dash lines to electrical cable.

3. Optical synchronization set-up

The experimental set-up is schematically depicted in Fig. 4. A 10 Gbit/s pulse stream is generated by an externally mode-locked laser. A 9.9538 GHz electrical signal is produced by a signal generator applied to an externally mode-locked laser and it is synchronized with a second signal generator at 1 GHz used as a trigger for a 50 GHz sampling oscilloscope. The 10 Gbit/s optical stream is launched into an optical signal multiplexer (OMUX), with an output at either $1\times, 2\times$ or $4\times$ of the initial bit-rate, allowing rates at 10, 20, 40 Gbit/s to be produced. The format of the injected signal is RZ, resulting in a strong power in the side-bands. The sequences injected correspond to a series of pulses which is ideal for clock recovery as the power in the side-band is maximal. The input data signal is injected via a circulator into the SP-DBR laser in self-pulsation regime as depicted earlier. The wavelength of the injected signal is critical to show the full potential of the SP-DBR laser. If the detuning between the wavelength of the data stream and the SP-DBR was close to 0 nm, this would result in limitations on the synchronisation potential of the SP-DBR laser for application such as O3R. Also, if the detuning is too small the synchronisation will be better but it may induce some modification of the laser spectra, for instance injection-locking. Furthermore, one application should consider that if the detuning between the injected wavelength and the modes of the SP-DBR is too large, synchronisation will not be achievable or only achievable at the cost of a large input power. To show the full potential of the device, the wavelength of the injected signal is chosen to be 1567 nm, at almost 10 nm above the SP-DBR central wavelength. The 0 dB m injected signal power is evaluated taking into account the coupling losses between the SP-DBR laser and the lensed fiber. The signal of the SP-DBR laser is transmitted from port 2–3 of the circulator and the optical signal is analyzed on either a 50 GHz photodiode connected to a 50 GHz sampling oscilloscope or a frequency resolved optical gating (FROG) system. The sampling time interval of the digital scope is 1 ps approximately. The FROG system assures a spectral resolution of 50 pm and a temporal resolution of 15 fs.

The optical spectrum of the 10 Gbit/s original signal is shown in Fig. 5, with a 0.07 nm resolution optical spectrum analyzer. The ripples appearing in the spectrum are spaced by 0.08 nm corresponding to a 10 GHz modulation.

Using the FROG technique, the pulses are analyzed in the temporal and spectral domains. The bias conditions of the SP-DBR laser sections are set to $I_g = 170.00$ mA and $I_B = 17.21$ mA, respectively. For the above current conditions the device gives a good response for all incoming data rates. However, assuming we are willing to vary bias conditions for each data rate, it is possible to fine tune bias levels according to one particular incoming pulse stream in

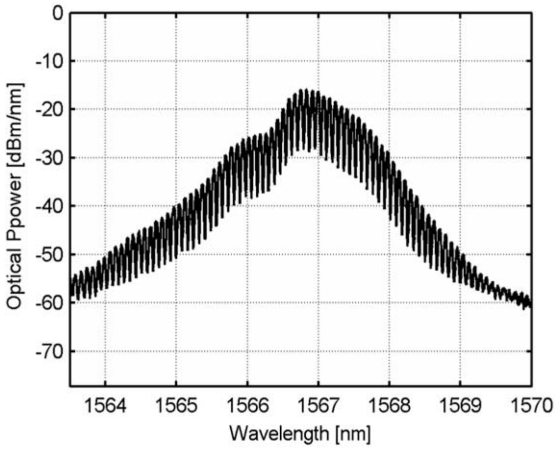

Fig. 5. Optical spectrum of a 10 GHz source signal from externally mode-locked tunable laser centered at around 1567 nm.

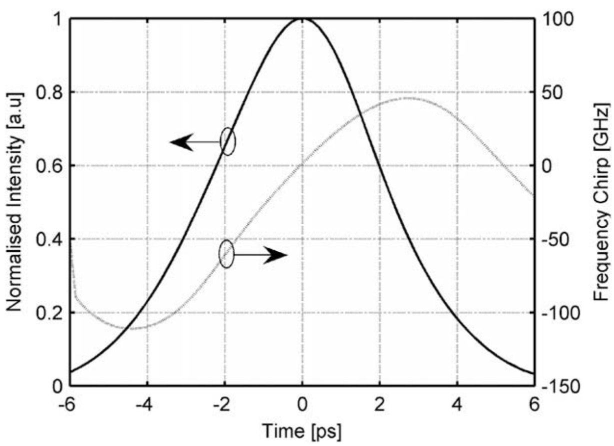

Fig. 6. Temporally resolved source pulse at 10 GHz with FROG system.

order to optimize the peak to valley ratio. With this technique, the pulse width has been measured at 5.29 ps for a 10 GHz repetition rate and its instantaneous frequency variation at 96.7 GHz as shown in Fig. 6. The overall time bandwidth product is equal to 0.512, which slightly differ from an ideal Gaussian pulse, i.e. 0.44. The pulses generated at 10 Gbit/s are quite symmetrical. They exhibit similar value of rise time and fall time. The extinction ratio of the source is 34.36, 32.82 and 32.82 dB for a bit-rate of 10, 20 and 40 Gbit/s, respectively. This figure also confirms that the modulation format is RZ. The pulse width is less than 5 ps for the 40 Gbit/s bit-rate. At this frequency a pulse in RZ format must not be larger than 8 ps, more than the pulsewidth of the signal we inject in the device. We should also mention that the presence of an offset does not have to be considered since the mechanism of synchronisation is based on the existence of tones close to the natural oscillation of the SP laser.

The 10 Gbit/s signal stream multiplexed by $1\times, 2\times$ and $4\times$ results in signals at 10, 20 and 40 Gbit/s, respectively. These signals, presented in Fig. 7 are measured by launching the output of the multiplexer into a 50 GHz bandwidth photodiode interfaced to a 50 GHz sampling oscilloscope. The signals are injected in the SP-DBR laser to synchronize its free running frequency. In the next section, optical synchronization is investigated. Evidences and characterisation of synchronization of the 39.7 GHz SP laser to various bit-rate from 10 to 40 Gbit/s are presented.

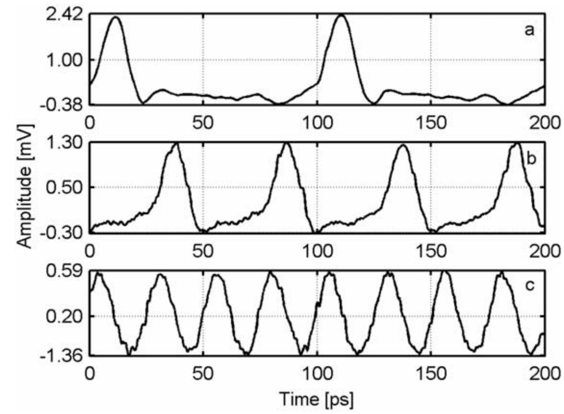

Fig. 7. Optical source signal at 10 (a), 20 (b), 40 Gbit/s (c), measured with a 2 mV offset.

4. Optical synchronization results

A variety of optical signals with bit-rates at 10, 20 and 40 Gbit/s are used to synchronize the fundamental frequency of the SP-DBR laser. In each case the 39.7 GHz free running signal of the SP-DBR laser is synchronised to the 39.82 GHz spectral component carried by the data stream. For 10 and 20 Gbit/s data rates the third and first harmonics of the signals are responsible for synchronization, for 40 Gbit/s it is the fundamental frequency.

The results are presented in the time domain using both a 50 GHz sampling scope and the decorrelation trace obtained from the FROG technique. In the frequency domain, the FROG was used to extract the output signal of the SP-DBR laser with and without injection. Therefore, it was possible to quantify the synchronization of this device with 40 Gbit/s signal and its sub-harmonics.

4.1. Time domain investigation

The temporal responses of the SP-DBR laser to the injected optical signals are presented in Fig. 8. For every bit-rate an additional periodic pattern is superimposed to the 40 Gbit/s trace which makes a direct measurement of the extinction ratio difficult.

The value of timing jitter measured out of the sampling scope decreases with an increase of the average injected power. It is measured at 2.5 ps with an average injected power of 0 dB m at a 40 Gbit/s bit-rate.

The study of the temporal behavior of the synchronized SP-DBR signal has also been carried out using the FROG technique. Fig. 9a

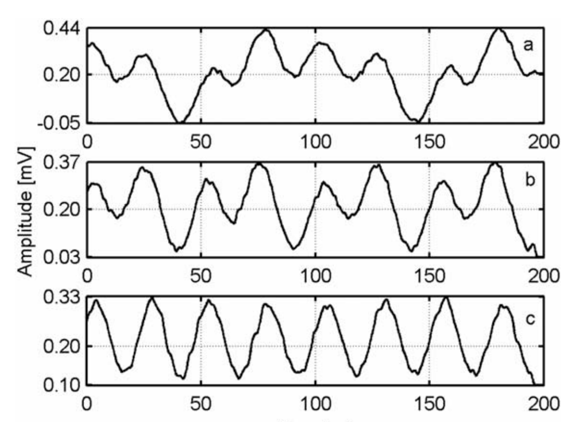

Fig. 8. Synchronized output signals at injected bit-rates of 10 (a), 20 (b), 40 (c) Gbit/s at 0 dB m of average power, measured with an offset of 2 mV.

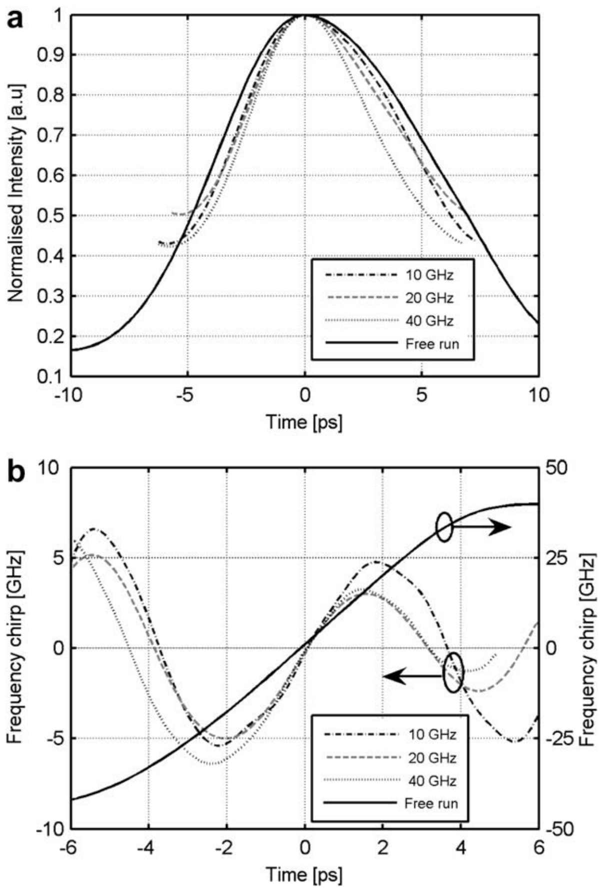

Fig. 9. (a) Intensity and (b) chirp of synchronized output signal pulse resolved temporally for free running (-.-) device and with a injected stream at 10 (-), 20 (..) and 40 (–) Gbit/s with a 0 dB m average injected power.

shows the time evolution of the SP-DBR laser output signals in free running condition and synchronized by the 10, 20 and 40 Gbit/s injected data stream. For all of these measurements the average power launched into the laser is 0 dB m. The pulse width of the 40 GHz emitted by the SP-DBR laser is almost invariant with the value of the bit-rate of the injected signal. This pulse width measurement confirms the results obtained with the sampling scope. It can also be found from Fig. 9a that the output signal is a periodic modulation with an extinction ratio of 2, rather than a pulse output; as the intensity does not reach the zero level.

In Fig. 9b the temporal evolution of the instantaneous frequency of the SP-DBR laser is shown in the free running condition and synchronized by the 10, 20 and 40 Gbit/s injected signals. The spectral excursion of the synchronized signal is less than 20 GHz in the worst case. At 40 Gbit/s with an average input signal of 0 dB m, the pulse width is 9.23 ps and a frequency bandwidth of 55.1 GHz, the time bandwidth product is 0.509, comparable to the original 10 Gbit/s signal presented in Fig. 6.

4.2. Optical spectrum investigation

Fig. 10a–c show the optical spectrum of the SP-DBR laser under an injected signal at 10, 20 and 40 Gbit/s bit-rate, respectively. The resolution of the optical spectrum analyzer is 80 fm and the average power injected in the SP-DBR laser is set at 0 dB m for any bit-rate injected. It can be observed that beside the original modes of the SP-DBR laser additional longitudinal modes appear in the spectra. The free spectral range (FSR) between those modes corresponds to the clock frequency of injected data stream.

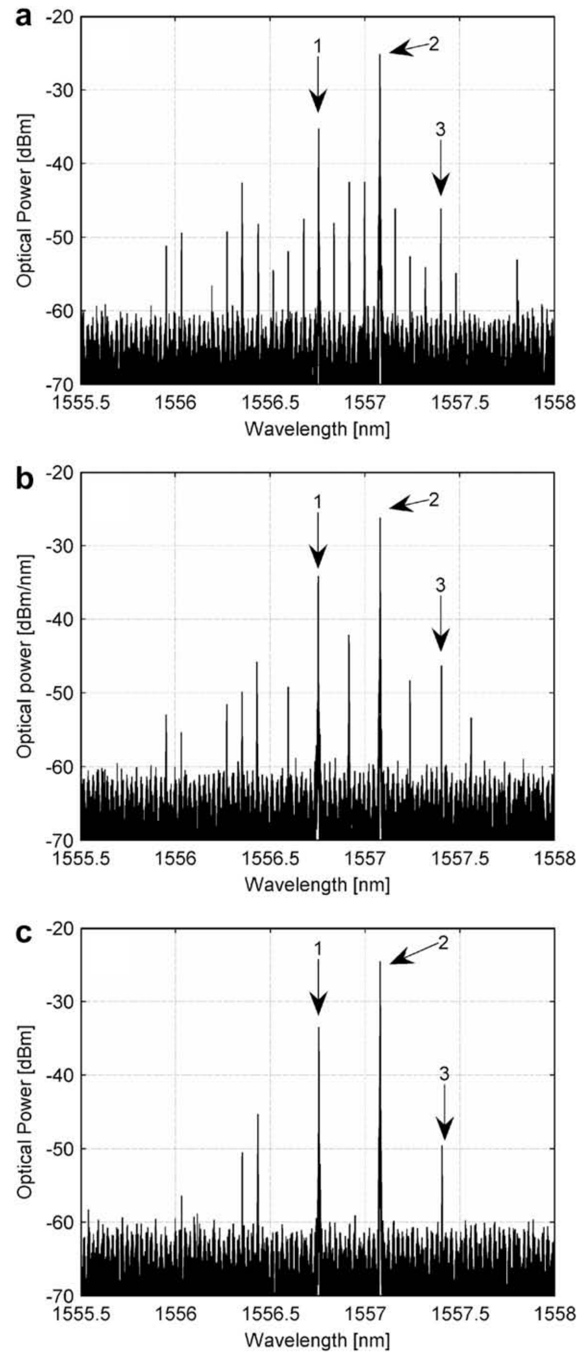

Fig. 10. High resolution optical spectra of the SP-DBR laser output signal biased with $I_g = 150$ mA, $I_B = 18.82$ mA for 0 dB m average power at a bit-rate of: (a) 10 Gbit/s, (b) 20 Gbit/s and (c) 40 Gbit/s. The arrows correspond to the original laser modes.

It has to be kept in mind that the optical signal injected has its peak at 1567 nm, hence 10 nm away from the mode of the SP-DBR laser. In Fig. 10a, three extra modes appear between two consecutive initial modes shown in Fig. 3 and referred to as 1, 2 and 3. The spectral separation between these extra modes corresponds to a mode beating of 10 GHz, matching the bit-rate of the injected signal. In Fig. 10b, only one extra mode appears between two consecutive modes of the original laser spectra. The FSR is 20 GHz, corresponding to 20 Gbit/s. In Fig. 10c. no extra mode is observed, this corresponds to a 40 Gbit/s injected. Hence, the injected data at 1567 nm leads to a modification of the optical spectrum of the SP-DBR laser according to the bit-rate injected. This proves that there

Table 1
Optical linewidth of the dominant mode measured for different injected data rates at a 0 dB m average injected power.

	Free running	Injected bit-rate (Gbit/s)		
		10	20	40
Linewidth (MHz)	74.1	40.4	43.8	43.8

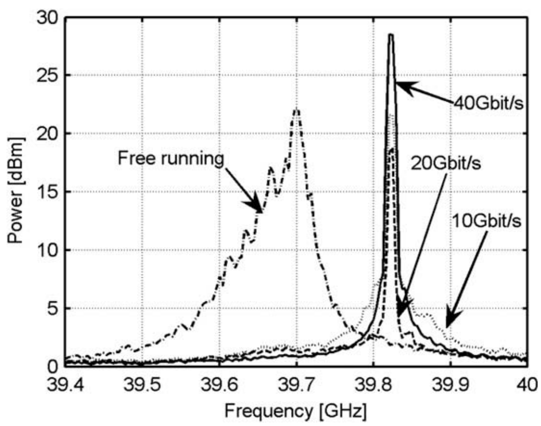

Fig. 11. Electrical spectrum recorded for the SP-DBR laser biased with $I_g = 181.83$ mA, $I_g = 1.75$ mA and 3 dB m. The average injected power of the external optical signal at 10, 20 and 40 Gbit/s is 0 dB m.

is synchronization of the SP-DBR laser to the bit-rate of the injected signal. More evidence of the synchronization is presented in Table 1.

Table 1 lists the linewidth of the dominant mode in free running conditions and for different injected bit-rates at a 0 dB m average injected power. The bias conditions of the equivalent spectrum have been mentioned above. It is clear that when the SP-DBR laser is synchronized to the incoming data signal, the linewidth of its dominant optical mode is drastically reduced. This confirms that there is synchronization of the SP-DBR laser as the phase noise is reduced. To further investigate the synchronization of the SP-DBR laser, the electrical spectra of the output signal in free running conditions and with injections are recorded.

4.3. Electrical spectrum investigation

The optical signal of the SP-DBR laser is launched into a 50 GHz photodiode and resolved with a 40 GHz ESA. For all injected signals, a shift from 39.7 GHz to 39.8 GHz is observed with a linewidth reduced from 30 MHz to 13 MHz as shown in Fig. 11. When the self-pulsating laser is synchronised, the self-pulsating frequency corresponds to the data rate, or a multiple of it around the free spectral range of the laser. In our case the frequency of the RF source used to generate the three data rates is 9.9538 GHz. In all three cases of bit-rates, a 4×9.9538 GHz RF signal is generated from the synchronized laser. Even, if it is not possible to conclude on the lock-in range of the device from this set of data, the change of RF frequency between a free running and synchronised device shows that the lock-in range can be estimated to be at least 100 MHz. As the resolution of measurement is 3 MHz the measured values of FWHM, when the SP-DBR laser is synchronized, must be deconvolved in order to achieve a more precise value of the linewidth. Furthermore, peak intensities may differ from real values. This is due to the fact that the resolution of the RF spectrum analyser is too close to the linewidth of the measured signal to find an accurate value of the peak. Due to this limitation of our ESA, only few points are taken around the signal. It is unlikely that any of these points correspond to the real maximum of the signal. Hence, the experimental maximum value measured does not correspond to the real value, which could be measured with a high resolution RF spectrum analyser. This also explains why the peak value for 10 Gbit/s is stronger than the 20 Gbit/s but lower than the 40 Gbit/s, which at first sight may not appear logical.

5. Conclusion

In this paper, we investigated the synchronization of a 40 GHz self-pulsating DBR laser to bit-rate of 10, 20 and 40 Gbit/s. The device features a periodic modulation of its optical output at 39.7 GHz even though it is DC biased and no external optical signal is injected. The origin of this phenomenon is due to the multimode spectrum of the device. We demonstrated its ability to synchronize its intrinsic 39.7 GHz modulation to the 10, 20 and 40 Gbit/s data signals. This all-optical clock recovery performance is mostly interesting as the data signal is detuned from the clock signal by almost 10 nm. It means that the SP-DBR can synchronise, with any detuning below 10 nm. It opens up a large range of applications such all-optical 3 R regenerators or all-optical logical gates, where the data stream and the clock signal may or may not be at the same wavelength.

The synchronized signal shows a smaller value of the range of its spectral excursion under modulation than that in free running. Its pulsewidth is of the same order, 10 ps and the RF linewidth of the synchronized signal is less than 15 MHz, half of that in free running. Further investigations should be performed on the stability of the synchronized signal with a random data signal injected.

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