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High-frequency signal generation using 1550 nm VCSEL subject to two-frequency optical injection

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ABSTRACT

We experimentally investigate high-frequency microwave signal generation using a 1550 nm single-mode VCSEL subject to two-frequency optical injection. We first consider a situation in which the injected signals come from two similar VCSELs. The polarization of the injected light is parallel to that of the injected VCSEL. We obtain that the VCSEL can be locked to one of the injected signals, but the observed microwave signal is originated by beating at the photodetector. In a second situation we consider injected signals that come from two external cavity tunable lasers with a significant increase of the injected power with respect to the VCSEL-by-VCSEL injection case. The polarization of the injected light is orthogonal to that of the free-running slave VCSEL. We show that in this case it is possible to generate a microwave signal inside the VCSEL cavity.

Keywords: Semiconductor lasers, vertical-cavity surface-emitting laser (VCSEL), optical injection, photonic microwave generation, radio-over-fiber (RoF), nonlinear dynamics.

1. INTRODUCTION

Photonic microwave sources producing highly stable and broadly tunable microwave frequencies are interesting for applications ranging from broadband wireless access networks and photonic microwave signal processing to emerging broadband photonics-based phased-arrays antennas and radars [1-2]. Microwave signal generation using photonics has the advantages of high speed, low power consumption, low cost and high reliability [3]. Large values of the propagation losses of high-frequency microwaves in free space makes the optical fiber a good choice to transmit an optical carrier that carries the microwave signal with large bandwidth and low loss over long distances [2]. Transmission of microwave signals over optical fibers has also the advantages of electromagnetic interference immunity and wavelength division multiplexing capability [4]. Different photonic microwave generation techniques include direct modulation of semiconductor lasers, optical mixing or optical heterodyning, external modulation using Mach-Zender modulators, mode-locked semiconductor lasers, and optically injected semiconductor lasers [2]. In the optical mixing scheme two optical waves detuned at a desired frequency beat directly at a photodetector to generate the microwave beat signal [5]. The generated RF frequency is only limited by the maximum response frequency of the photodetector. However the beat signal has large phase noise if the two optical beams are not phase correlated. The use of optical phase lock loops (OPLLs) has demonstrated optical beams with locked phases, and hence RF signals with high spectral purity. However OPLLs need a microwave reference source for phase stabilization and sideband generation which significantly increases the cost and complexity of the system [6]. Also dual-wavelength fiber lasers can be used to increase phase correlation between two lasing wavelengths because they share the same laser cavity [2]. Dual-wavelength fiber lasers can be obtained by using a filter in the laser cavity to select the lasing modes. In these systems frequency tuning is achieved through meticulous mechanical or thermal adjustments [4].

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Photonic microwave generation techniques based on the period-one (P1) nonlinear dynamics of optically injected semiconductor lasers have also attracted a lot of interest [2], [4], [7-10]. This approach allows widely tunable, optically controlled and single sideband generation of microwave signals [2]. P1 oscillation can be viewed as the beating of two dominant wavelengths: one is regenerated from the optical injection while the other is emitted near the cavity resonance wavelength [7]. The generated frequency range far exceeds the intrinsic relaxation oscillation frequency of the semiconductor laser. Photonic microwaves based on P1 dynamics have reached frequency values beyond 100 GHz [8] with a tuning range that is limited to several tens of GHz [6]. The generated microwave has a relatively large linewidth on the order of a few megahertz. A double-lock technique using a stable electronic microwave source has been used to obtain a RF linewidth below 1 kHz [10]. Generation of a microwave signal with simultaneous high frequency and low phase noise has been recently obtained by using the P1 dynamics of an optically injected DFB laser subject to a dual-loop optical feedback [4]. Photonic generation at 45 GHz with a linewidth below 50 kHz has been demonstrated in a laser with just 7 GHz relaxation oscillation frequency [4].

Very recently, microwave generation using dual-beam optical injection in semiconductor lasers has also been investigated [6], [11-15]. Microwave signals with frequencies corresponding to the frequency difference between the master lasers can be generated [6], [11], [14]. This optical injection scheme does not require a microwave reference source. It has also the advantages of low system complexity, narrow linewidth, low cost, single sideband generation, small power fluctuations, and a much broader tuning range than the single-beam injection scheme [6], [13]. A very high frequency (121.7 GHz) microwave signal has been generated by using a dual-beam optically injected single-mode DFB laser [6]. 'Double injection locking' is observed when the slave laser is subject to strong optical injection by both master lasers in such a way that stable locking is also observed if only light from one of the master lasers is injected [6], [13]. Comparison of the performance with a similar P1 oscillation signal generated with single optical injection shows that a significant reduction of the linewidth is achieved when using the 'double injection locking' scheme due to the phase-locking and high coherence associated to stable injection locking states [13]. Similar photonic microwave generation using VCSELs instead a DFB laser has also been recently considered in a theoretical way [14,15]. Single and multi-transverse mode VCSELs subject to two-frequency optical injection can generate high-frequency microwave signals [14]. The response of multi-transverse mode VCSELs is larger than that obtained with similar single-transverse mode devices due to the significant excitation of high-order transverse modes. In this way, while for single-frequency injection, excitation of a second longitudinal mode is detrimental for generating microwave signals [2], for two-frequency injection, excitation of a second mode can be beneficial [14].

In this work we experimentally investigate high-frequency microwave signal generation using a 1550 nm single-mode VCSEL subject to two-frequency optical injection. We first consider a situation in which the injected signals come from two similar VCSELs. Recent experimental work has demonstrated single-mode [16] and multimode [17] VCSEL-by-VCSEL optical injection locking. In our initial system the polarization of the injected light is parallel to that of the injected VCSEL. We show that microwave signals with frequencies up to 49 GHz are obtained. However, the generated RF power is small and the signal is attributed to beating in the photodetector. We consider then a second situation in which injected signals come from two external cavity tunable lasers with a significant increase of the injected power with respect to the VCSEL-by-VCSEL injection case. In this second experiment the polarization of the injected light is orthogonal to that of the free-running slave VCSEL. The theoretical study of this case has shown that the microwave signal generation mechanism is independent of the polarization of the master lasers [15]. Our results show that the VCSEL can emit in the two master laser frequencies. A microwave signal with significant RF power corresponding to the previous situation is demonstrated with 11.3 GHz frequency.

2. VCSEL-BY-VCSEL PARALLEL OPTICAL INJECTION

The experimental set up is shown in Fig. 1. The Slave Laser (SL) and the two Master Lasers (ML1, ML2) are commercially available fiber pigtailed VCSELs (Raycan) emitting in the 1550 nm region. Each laser was temperature controlled with a Thermo Electric Cooler (TEC) and all measurements were performed at a constant temperature of 25º C. Light from ML1 and ML2 entered an Optical Isolator (OI) in order to avoid unwanted back reflections into the master lasers and an anti reflection gel was used in fiber connections to minimize the effect of reflections along the fiber path. Polarization Controllers (PC) were used for each master laser in order to adjust the polarization state of ML1 and ML2 to the polarization state of the SL. The VCSELs used in the experiments have threshold currents around 1.5 mA, and show Polarization Switching (PS) between stable linear polarization states oriented in orthogonal directions when the bias current is increased. Each linear polarization corresponds to a lasing mode due to birefringence between the two polarization axes. Polarization modes are spaced about 0.1 nm (12.5 GHz) as observed with spectral measurements under threshold. In the two-frequency optical injection experiments, the driving currents of the three VCSELs have been chosen in order to have stable linear polarization states in all the devices.

A Variable Optical Attenuator (VOA) was used to control the injected power from each master laser (ML1 and ML2) and 10% of the output power of each VOA was measured with a Power Meter (PM1 and PM2). The 90% of the power from the VOAs was sent to the input ports of a 50:50 fiber coupler and injected into the SL through an Optical Circulator (OC). The signal at port 3 of the OC entered a 50:50 fiber coupler and was sent to the Optical Spectrum Analyzer (OSA, Ando AQ6315 with 6.25 GHz bandwidth resolution) and to a 45 GHz bandwidth photodiode (PD, New Focus 1014) connected to the Electrical Spectrum Analyzer (ESA, Agilent N9030A, 3 Hz - 50 GHz).

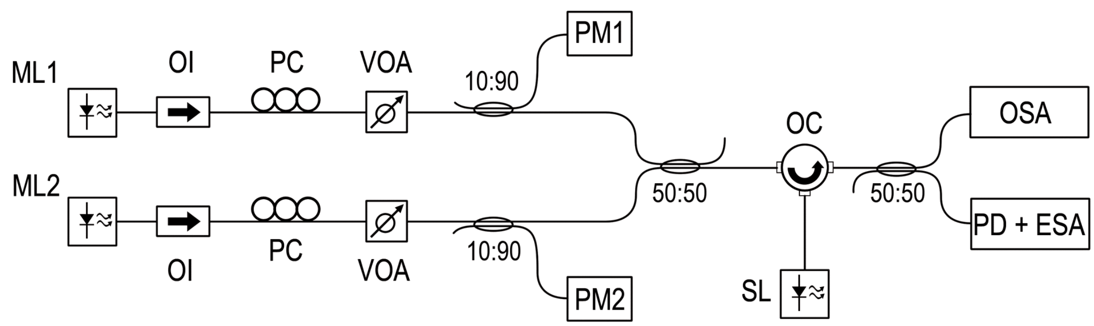

Figure 1. Experimental setup. Details are given in the text.

We now present the results obtained with the two-frequency optical injection given by two single-transverse mode VCSELs on a similar single-transverse mode VCSEL. First, we present an experiment in which the SL is frequency locked to the ML1 and a RF signal at 46 GHz is generated when the light from the ML2 is also injected into the SL. We define the frequency separation between the frequencies of the two master lasers, as $\Delta f_{MM} = f_{ML2} - f_{ML1}$, and the frequency detuning of the ML1 with respect to the SL frequency as $\Delta f_{MS} = f_{ML1} - f_{SL}$, where f_{ML1}, f_{ML2} and f_{SL} are the optical frequencies of the ML1, the ML2 and the SL under free running operation, respectively.

The free running spectra of the VCSELs were measured by biasing one VCSEL at time and taking the corresponding spectrum at the OSA. The threshold currents of ML1, ML2, and SL VCSELs are 1.51 mA, 1.49 mA and 1.53 mA, respectively. The driving current of the SL, I_{SL}, was fixed at 4.0 mA for all the experiments, corresponding to a free running emission wavelength of 1538.09 nm. The master lasers were fed with bias currents I_{ML1} = 5.6 mA and I_{ML2} = 6.0 mA, corresponding to free running emission wavelengths of 1538.02 nm and 1538.38 nm from ML1 and ML2, respectively. Under these conditions, Δf_{MS} = 8.5 GHz and Δf_{MM} = -45.6 GHz. The optical spectra of the three free running VCSELs are shown in Fig. 2 (a). The peak amplitudes of ML1 and ML2 are approximately 10 dB weaker than the SL peak amplitude, as expected considering that the light from the MLs is reflected at the SL cavity.

The optical spectrum under double frequency injection, when I_{SL} = 4.0 mA, I_{ML1} = 5.6 mA and I_{ML2} = 6.0 mA, is shown in Fig. 2 (a). Under these conditions, the injected power from ML1 and ML2 are P_{ML1} = 234 μW and P_{ML2} = 360 μW, respectively. The optical spectrum consists of two well defined peaks at f_{ML1} and f_{ML2}. The SL is locked to the frequency of the ML1 and in consequence, both the SL and the ML1, emit at the free running emission wavelength of ML1 and with the polarization of ML1. Frequency locking of the SL has been also checked at the ESA, observing a plain spectrum when the SL is subjected to optical injection only from ML1, in the same conditions.

The electrical spectrum obtained with the double frequency injection from ML1 and ML2 is shown in Fig. 2 (b). A Radio Frequency (RF) signal can be observed at 46 GHz, corresponding to the frequency separation between ML1 and ML2, Δf_{MM} = -45.6 GHz (0.36 nm). The RF signal at 46 GHz has a narrow FWHM bandwidth, as it can be noted from the inset of Fig. 2 (b), where an enlarged view of the measured signal is shown. Fluctuations in the value of the central frequency of 0.1-0.2 GHz have been observed and are attributed to the current and temperature instabilities of the three laser drivers which affect the emission wavelength of the VCSELs.

High frequency signal generation in single transverse mode VCSELs has been studied theoretically by Quirce et al. [14], showing that high-frequency microwave signals can be obtained in these devices. However, in this case, we consider that the observed microwave is the beating signal of the light emitted by the SL and the light of ML2 that is reflected at the SL. This is clear from Fig. 2(a) in which the long-wavelength peak of the optical spectrum of the two-frequency injected SL coincides with the free running ML2 spectrum, and hence the power emitted by the SL at the ML2 frequency is very small. The absence of internally generated microwave signal is due to the low values of the injected power that cause the SL to emit only in a single frequency, the ML1 frequency. In the next section we will consider larger values of injected powers in order the SL to emit simultaneously with ML1 and ML2 frequencies.

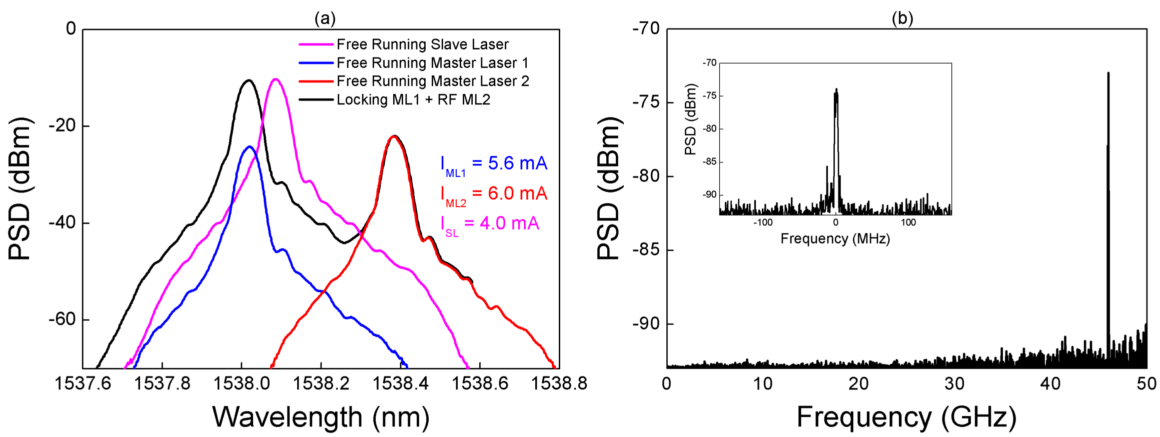

Figure 2. Optical spectrum (a) of the free running ML1 (blue line), ML2 (red line) and SL (magenta line) and of the two frequency injected SL (black line), with I_{SL} = 4.0 mA, I_{ML1} = 5.6 mA and I_{ML2} = 6.0 mA. Electrical spectrum (b) obtained from the two frequency injected SL under the same conditions. The frequency axis of the inset in (b) is centered at the RF peak frequency.

We found that previous result (frequency locking of the SL but absence of P1 oscillations) was independent of the frequency spacing Δf_{MM} between the two MLs. In our experiments, the SL is locked to the ML1, with Δf_{MS} = 8.5 GHz and P_{ML1} = 234 μW, and the frequency detuning Δf_{MM} is varied by changing the emission wavelength of ML2 through its driving current I_{ML2}. The wavelength tunability of the VCSELs is about 44 pm/mA. Different frequencies have been observed by varying I_{ML2}, from 4.4 mA to 5.1 mA, which corresponds to sweep the emission wavelength of ML2 from 1537.64 nm to 1537.96 nm and Δf_{MM} between 9 and 49 GHz. The electrical and optical spectra obtained are shown in Fig. 3 (a) and (b), respectively. The optical spectra show that the SL is emitting in a single mode and that the peak at lower wavelengths corresponds to the reflection of the ML2 in the SL, and therefore the microwave signal is generated in the photodiode.

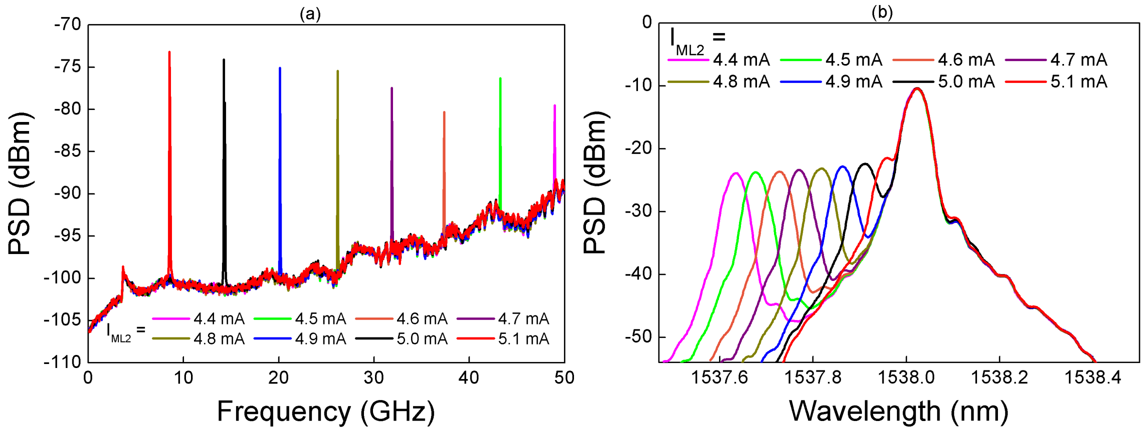

Figure 3. Electrical (a) and optical (b) spectra obtained with I_{SL} = 4.0 mA, I_{ML1} = 6.0 mA, corresponding to Δf_{MS} =8.5 GHz and P_{ML1} = 234 μW, for different values of I_{ML2} between 4.4 mA and 5.1 mA.

Similar results were obtained by tuning the ML2 to frequencies lower than that of ML1 within the range -45 GHz < Δf_{MM} < -9 GHz, corresponding to ML2 currents between 5.4 and 6 mA, as it can be observed in Fig. 4. The exception was for I_{ML2} = 5.5 mA, which corresponds to Δf_{MM} = 15.4 GHz and P_{ML2} = 333 μW. In this case the emission peak of ML2 is enhanced with respect to the adjacent peaks at 5.4 mA and 5.6 mA, as shown in Fig. 4 (b). This is attributed to the coupling of the suppressed orthogonal polarization mode of the SL (expected at about 12.5 GHz at longer wavelength) to the dominant parallel polarization mode of the ML2. The RF signal at 15 GHz for I_{ML2} = 5.5 mA could be due to P1 generation instead of beating at the photodetector, although it is difficult to differentiate both origins.

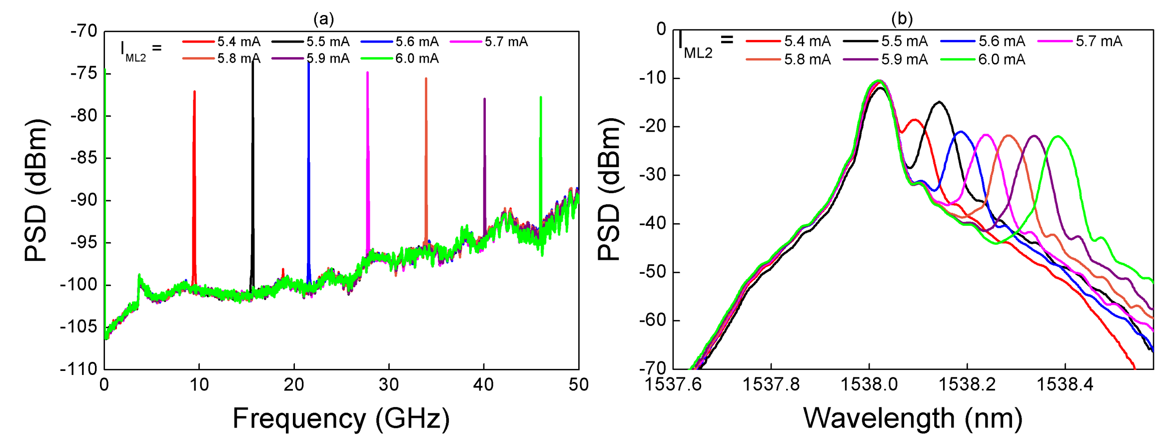

Figure 4. Electrical (a) and optical (b) spectra obtained with I_{SL} = 4.0 mA, I_{ML1} = 6.0 mA, corresponding to Δf_{MS} =8.5 GHz and P_{ML1} = 234 μW, for different values of I_{ML2} between 5.4 mA and 6.0 mA.

When I_{ML2} is set to 5.2 mA and 5.3 mA, corresponding to nominal detuning between the MLs Δf_{MM} = 2.25 GHz and Δf_{MM} = - 3.25 GHz, respectively, the SL exits the stable frequency locked regime and the well define RF peak at Δf_{MM} is no longer generated. The electrical and optical spectra obtained with I_{ML2} = 5.2 mA and I_{ML2} = 5.3 mA are shown in Fig. 5 (a) and (b), respectively. For I_{ML2} = 5.2 mA, a broad electrical spectrum below 10 GHz is obtained, which is attributed to chaotic dynamics in the injected VCSEL. For I_{ML2} = 5.3 mA, the electrical spectrum is characterized with several peaks below 20 GHz, spaced about 2-3 GHz, probably due to irregular dynamics, as suggested by the broadened optical spectrum. A complete study of the dynamics of the two frequency injected VCSEL in the detuning range of a few GHz is out of the scope of the present work, as we center our effort on the generation of high frequency RF signal, when the SL is frequency locked to one of the MLs.

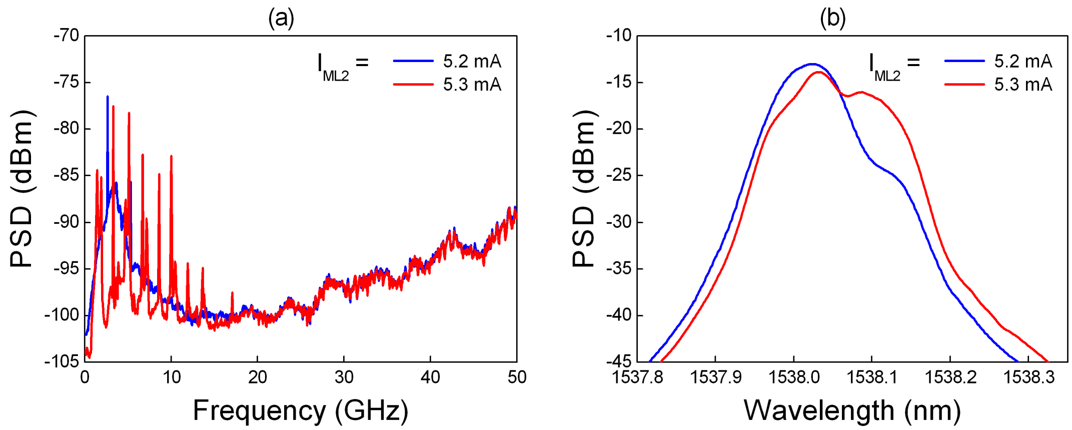

Figure 5. Electrical (a) and optical (b) spectra obtained with I_{SL} = 4.0 mA, I_{ML1} = 6.0 mA, corresponding to Δf_{MS} =8.5 GHz and P_{ML1} = 234 µW, for I_{ML2} = 5.2 mA and I_{ML2} = 5.3 mA.

3. RESULTS FOR STRONG ORTHOGONAL OPTICAL INJECTION.

In this section we consider a different experimental setup in which MLs are no longer VCSELs but tunable external cavity lasers with higher emitted powers. Injected powers from ML1 and ML2 (Tunics Plus CL) are P_{ML1} = 1.92 mW and P_{ML2} = 4.35 mW, respectively. The SL is a single-transverse mode VCSEL with a threshold current around 1.5 mA that shows PS under CW operation at around 6 mA. The optical spectrum of the free-running VCSEL biased at 4 mA is shown with a cyan line in Fig. 6(a). The spectrum has two peaks that correspond to the two orthogonal polarizations of the fundamental transverse mode of the device. The lasing mode is located at a wavelength of 1537.92 nm and has a direction that we will call parallel. The subsidiary mode has orthogonal polarization and its wavelength is shifted 0.24 nm (30 GHz) to the long-wavelength side of the lasing mode. Polarization controllers are adjusted in such a way that the direction of the polarization of the injected light is the orthogonal one. Optical spectrum of the free running ML1 and ML2 are shown with blue and green lines, respectively. Free running emission wavelengths of ML1 and ML2 are 1538.15 nm and 1538.24 nm, respectively. Under these conditions Δf_{MM} = -11.25 GHz and Δf_{MS} = 1.25 GHz, where Δf_{MS} is now the frequency detuning of ML1 with respect to the orthogonal polarization of the SL, $\Delta f_{MS} = f_{ML1} - f_{SL,\perp}$, as defined in [15]. The optical spectrum under double frequency injection is also shown in Fig. 6(a) with a red line. The optical spectrum consists of two well defined peaks at λ_{ML1} and λ_{ML2}. PS is observed in the SL VCSEL because both injected wavelengths are close to the orthogonal polarization wavelength of the device. Also both long-wavelength peaks of the optical spectrum of the two-frequency injected SL are clearly larger than those peaks that correspond to the reflected light of free running ML1 and ML2 at the VCSEL's mirror. This indicates that the VCSEL is now emitting in two frequencies, in contrast to what was observed in Fig. 2(a). The corresponding electrical spectrum obtained with the double frequency injection from ML1 and ML2 is shown with a red line in Fig. 6 (b). A Radio Frequency (RF) signal has been generated at 11.3 GHz, corresponding to the frequency separation between ML1 and ML2, Δf_{MM} = -11.25 GHz. The generated RF power is much larger than in Fig. 2(b). Fig. 6(b) also includes the electrical spectrum obtained when the SL is off, signal that corresponds to beating in the detector of the reflected lights from free-running ML1 and ML2. An increase of 5 dB is observed in the RF peak when two-frequency optical injection is considered. Not very different RF linewidths are observed when the VCSEL is on and off. Measurements with better frequency resolution are planned in the near future for getting a better comparison between both RF linewidths. Our results show that microwave signal generation using dual beam optical injection not only works when parallel optical injection is used [6] but also when orthogonal optical injection is considered. This indicates that the proposed microwave generation mechanism is independent on the polarization of the master lasers, in agreement with [15].

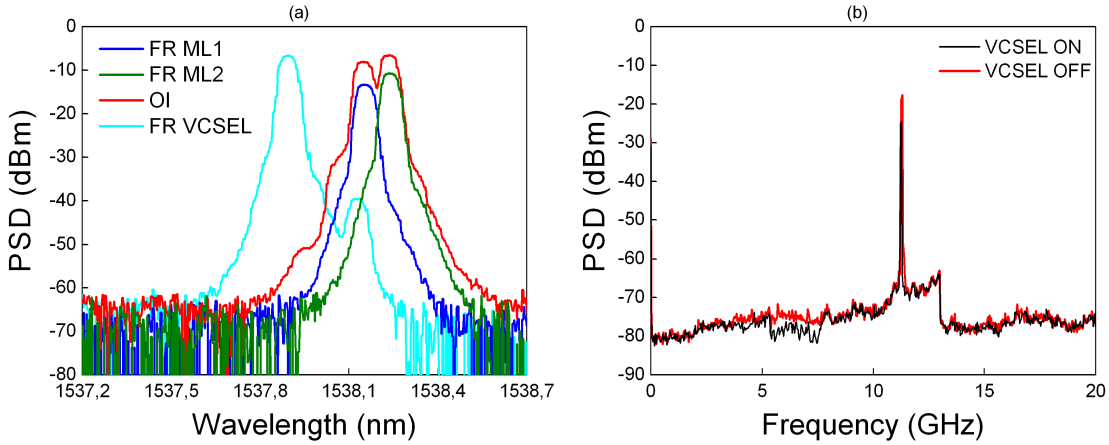

Figure 6. Optical spectrum (a) of the free running ML1 (blue line), ML2 (green line) and SL (cyan line) and of the two frequency injected SL (red line), with I_{SL} = 4.0 mA, λ_{ML1}= 1538.15 nm and λ_{ML2} = 1538.24 nm. Electrical spectrum (b) obtained from the two frequency injected SL (red) and from the same set-up but with the SL off (black).

Fig. 7 shows similar optical spectra to those of Fig. 6 but when the ML wavelength is increased to λ_{ML2}= 1539.73 nm (Δf_{MM} = -297.5 GHz). Similarly to Fig. 6(a) the optical spectrum under double frequency injection consists of two well defined peaks at λ_{ML1} and λ_{ML2}. Again PS is observed in the SL VCSEL as in Fig. 6(a). However the qualitative situation changes because the long-wavelength peak of the optical spectrum of the two-frequency injected SL coincides with the free running ML2 spectrum, similarly to Fig. 2(a): the VCSEL is then emitting in a single frequency and the generated microwave signal is due to the beating of the light emitted by the SL and the light of ML2 that is reflected at the SL. We can not observe the corresponding peak in the electrical spectrum because it would appear at a frequency much larger than the bandwith of our photodetector. A more detailed characterization of the dependence of the microwave signals on the detuning and injected power level will be further reported.

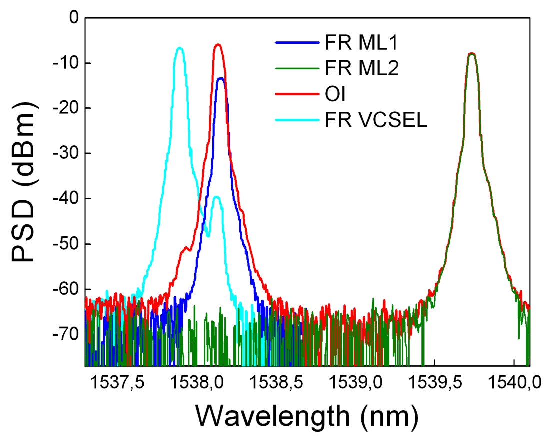

Figure 7. Optical spectrum of the free running ML1 (blue line), ML2 (green line) and SL (cyan line) and of the two frequency injected SL (red line), with I_{SL} = 4.0 mA, λ_{ML1}= 1538.15 nm and λ_{ML2} =1539.73 nm.

4. SUMMARY AND CONCLUSIONS

In this work we have made an experimental study of the photonic microwave signal generation obtained when single transverse mode VCSELs are subject to two-frequency optical injection. We have observed that the proposed microwave signal generation system is independent on the polarization of the master lasers. The results show that when the injected power is low it is possible to lock the emission frequency of the SL to the frequency of the injected signal, but it appears to be difficult to generate microwave signal by inducing P1 oscillation. However, we have shown that it is possible to generate P1 at higher injected power and for particular detuning range. Our experimental results are in agreement with the theoretical results obtained in [14-15]. Further theoretical and experimental work would be of interest for elucidating the different dynamics that can be obtained in this system.

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