We report class-A dual-frequency oscillation at 1.55 μm in a vertical external cavity surface emitting laser with more than 100 mW optical power. The two orthogonal linear polarizations of different frequencies oscillate simultaneously as their nonlinear coupling is reduced below unity by spatially separating them inside the active medium. The spectral behavior of the radio frequency beatnote obtained by optically mixing two polarizations and the phase noise of the beatnote have been explored for different coupling strengths between the lasing modes. © 2014 Optical Society of America

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Class-A dual-frequency VECSEL at telecom wavelength

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Optical generation of microwaves and millimeter-wave signals is emerging as a key building block for future optoelectronic communication systems such as broadband mobile systems [1], satellite networks [2], short-range video transmission [3], long-range transmission of high-purity radio frequency (RF) references [4], wide-band radar signal processing [5], and so on. To be useful for an optoelectronic system, the optically carried microwave tone should have very narrow linewidth, good spectral purity, continuous tunability over a wide range, and 100% modulation depth. Finally the generating system should be compact, and the optical wavelength has to lie in the telecom range. There are several techniques to generate optically carried microwave signals, such as direct or external modulation of a single-mode laser, optical mixing of two lasers or two longitudinal modes of a single laser, mode locking of semiconductor lasers, and so on. However, all these techniques suffer from different drawbacks, such as poor modulation depth, requirement of a bulky and expensive RF signal generator for external modulation of a laser, large bandwidth of the RF signal generated by heterodyning two lasers, and poor tunability of the RF signal obtained from optical mixing of two longitudinal modes of a single laser. Dual-frequency lasers, sustaining simultaneous oscillation of two orthogonal linear polarizations of different frequencies, have the capability to overcome all these shortcomings of the previously mentioned techniques, and can provide high spectral purity, wide tunability, and 100% modulation depth of the optically carried microwave signal.

Such dual-frequency oscillation has been achieved for different solid-state active media (mainly Nd3+- and Er3+-doped), optically pumped by diode lasers [6–8]. However, due to the inherent class-B dynamical behavior of these solid-state lasers [9], they suffer from relaxation oscillations (ROs), which severely degrade the spectral purity of the RF beatnote, especially at RO frequencies. To overcome these ROs, dual-frequency oscillation has been realized in a vertical external cavity surface emitting laser (VECSEL), having class-A dynamical behavior as the photon lifetime inside the centimeter-long external cavity is larger than the carriers’ lifetime [10]. The intensity and phase noise properties of such dual-frequency VECSEL (DF-VECSEL), and its influence on the spectral purity of the generated optical microwave, have been already demonstrated [11–13]. However, in the previously mentioned cases, the DF-VECSEL is operating either at 1 μm or 852 nm, rendering it incompatible with most microwave photonics applications. Besides, a high power and ultralow noise single mode VECSEL operating at 1.55 μm has recently been realized [14]. In this Letter, we demonstrate a DF-VECSEL at 1.55 μm having high power and very low noise, that hence would be able to optically generate high spectral purity microwave signals.

The schematic of our DF-VECSEL is depicted in Fig. 1. The laser operating at 1.55 μm is based on a 1/2-VECSEL structure [15]. This structure consists of an InP-based active region, including eight strained InGaAlAs quantum wells distributed among three optical standing wave

![DF-VECSEL architecture](image)

**Fig. 1.** DF-VECSEL architecture. d, spatial separation between ordinary (o) and extraordinary (e) polarizations inside the active medium; BC, birefringent crystal; L, collimating lens; BS, beam splitter; λ/2, half-wave plate; OI, optical isolator; FPI, Fabry–Perot interferometer; OSA, optical spectrum analyzer.
anti-node positions with 4-2-2 distribution. There is a 17-pair metamorphic GaAs/AlGaAs semiconductor Bragg mirror, whose reflectivity is larger than 99.9% at 1.55 μm thanks to the deposition of a gold layer. The overall gain structure is bonded on a chemical vapor deposition (CVD) polycrystalline diamond substrate. A quarter-wavelength SiN antireflection (AR) layer at the pump wavelength is finally deposited on the sample surface. Before that, the thickness of the top InP layer acting as a phase layer is etched, so that the position of the resonant mode of the 1/2-VECSEL microcavity nearly coincides with the gain maximum after AR layer deposition. The temperature of the 1/2-VECSEL structure is controlled at 20°C using a Peltier thermoelectric cooler. The gain structure is optically pumped with a continuous wave (CW) multimode fiber coupled 980 nm diode laser delivering up to 4 W optical power with an incidence angle of about 40°. The optical length of the laser cavity is 4.88 cm, which leads to a free spectral range (FSR) of 3.073 GHz. The cavity is closed with a concave mirror with 99.4% reflectivity at 1.55 μm, and radius of curvature of 5 cm. The waist size of the two laser modes on the gain structure is calculated to be 61 μm. The pump spot size on the gain structure is adjusted to have maximum and nearly identical power for the two linear orthogonal polarization modes. If we consider that the optical losses inside the cavity are predominantly coming from the output coupler only (0.6% transmittivity), then the intracavity photon lifetime should be equal to 55 ns. Even taking intracavity losses into account, it is much larger than the carrier lifetime (typically a few hundreds of ps under lasing conditions) in the 1/2-VECSEL structure. This ensures class-A dynamical behavior of our DF-VECSEL which hence does not suffer from ROs.

To reach simultaneous and robust oscillation of two linear orthogonal polarizations of different frequencies, we need to reduce the strength of nonlinear coupling between the modes inside the gain medium [16]. In our case, simultaneity is achieved by spatially separating the two polarizations on the gain structure with a thin intracavity YVO₄ birefringent crystal (BC), cut at 45° with respect to its optical axis, and AR coated at 1.55 μm. To vary the coupling strength between the modes, we used two different thicknesses for BC, namely 1 and 0.5 mm, which, respectively, correspond to spatial separations of 100 and 50 μm between the modes inside the gain structure. Moreover, a 150 μm thick uncoated glass etalon located between the intracavity BC and the output coupler forces each polarization to be longitudinally monomode (Fig. 1).

The optical spectrum of our DF-VECSEL is recorded with an optical spectrum analyzer, and is reproduced in Fig. 2(a). The two peaks in the spectrum prove the presence of two modes of different frequencies centered around 1.55662 μm. The output of the DF-VECSEL is also analyzed with a Fabry–Perot interferometer (FSR = 10 GHz) followed by an oscilloscope. The temporal signal recorded with oscilloscope, shown in Fig. 2(b), again confirms stable dual-frequency oscillation of our laser without any mode hopping during several tens of minutes.

Let us discuss the optimal value for the separation d between the modes. On the one hand, a large spatial separation between the modes is desirable for good robustness, as stable simultaneous oscillation of two modes requires the coupling constant C [11] to be much smaller than unity. On the other hand, a smaller separation between the modes increases the laser efficiency, since the pump beam can be more tightly focused for identical and optimal pumping of the two modes. This latter effect is visible in Fig. 3, which shows the variation of total output power of the two modes of the DF-VECSEL with the pump power variation. The black squares are obtained for the 0.5 mm thick BC, whereas the red circles correspond to the 1 mm thick BC. As expected, the laser is more efficient for the smaller value of d. In both cases, the laser power starts to saturate for pump powers higher than 2 W, due to thermal effects, and increasing spectral mismatch between the gain maximum and the microcavity resonance at higher pump powers [16]. In spite of the intracavity losses and the spatial separation of the two beams reducing the overlap with the pump, we can obtain more than 100 mW of optical power from our DF-VECSEL, with an intracavity BC of thickness 0.5 mm and for a pump power around 2.5 W (Fig. 3). In both cases, the total laser power is almost equally distributed among the two modes.

We tried to further reduce d by using a 0.2 mm thick crystal, corresponding to d = 20 μm. However, in this case, we observed that the dual-frequency regime becomes quite unstable, showing that the coupling between the two modes is too strong. Therefore, probably 0.5 mm is not far from being the optimal thickness for BC in the case of our laser cavity.

We measured the phase noise of the generated RF beatnote using the experimental setup depicted in Fig. 4.
The RF beat signal is obtained by optically mixing the two orthogonal linear polarizations using a polarization beam splitter (PBS) following a half-wave plate (λ/2-plate). The beat frequency depends on the FSR of the cavity, and the intracavity phase anisotropy introduced by the BC. Hence, the RF beat signal can be adjusted over a wide range by rotating the BC and/or the intracavity étalon. The RF beatnote signal is detected using a high-speed photodiode and amplified. Its spectrum can be recorded using an electrical spectrum analyzer (ESA). To measure its phase noise, the signal is down-shifted to intermediate frequency (IF) by mixing it with a local oscillator (LO) having a very low phase noise. Thereafter, the IF signal is recorded in time domain using a deep memory digital oscilloscope. Finally, the oscilloscope data are numerically processed to obtain RF phase noise spectra.

We measured the beatnote spectra and the RF phase noise for the two different BCs of thicknesses 1 and 0.5 mm. The results for 1 mm thick BC, which corresponds $d = 100 \mu m$, are shown in Fig. 5. Figure 5(a) shows the RF beatnote spectrum, measured with an ESA with resolution bandwidth (RBW) and video bandwidth (VBW) equal to 10 kHz. The beat signal is centered at about 4.3225 GHz. Because of class-A dynamical behavior of our DF-VECSEL, there is no side peak due to excess noise induced by ROs. This greatly improves the spectral purity of the RF signal generated by our DF-VECSEL compared to dual-frequency erbium lasers [4]. However, the beat signal of bandwidth less than 10 kHz is sitting on a few megahertz wide noise pedestal. This pedestal is coming from the phase fluctuations. The phase noise spectrum of the RF beatnote at frequencies ranging from 100 kHz to 10 MHz is shown in Fig. 5(b). If we closely observe the RF phase noise spectra, we can find a change of slope at about 300 kHz. We attribute this to the fact that the physical mechanisms responsible for the phase fluctuations might not be the same for frequencies higher and lower than 300 kHz. For frequencies higher than 300 kHz the phase noise is expected to come mainly via phase-intensity coupling, due to the high Henry factor [17] of semiconductor active medium, whereas within frequencies from 1 to 300 kHz, thermal fluctuations of the refractive index of the active medium induced by the pump intensity fluctuations is the probable dominant source [12]. The noise in excess appearing for frequencies lower than 1 kHz can be attributed to technical noises.

The experimental results for RF beatnote and phase noise measurements for the 0.5 mm thick BC, shown in Fig. 6, confirm this behavior. In this case, $d = 50 \mu m$, and hence the overlap between the two modes profile is large (about 50%), and the coupling is higher compared to the previous case. The RF beatnote is now centered at about 2.593 GHz, as shown in Fig. 6(a). Again, the spectrum is free from peaks coming from RO, confirming again the class-A nature of the DF-VECSEL. The RF phase noise spectrum of Fig. 6(b) exhibits the same features as in Fig. 5(b); a change of slope around 300 kHz corresponding to the transition between thermal noise induced in the structure by pump power fluctuations, and transfer of intensity to phase noise due to the large Henry factor of the semiconductor active medium. Below 1 kHz, again, the technical noises become dominant. Finally, if we compare the results of 1 and 0.5 mm thick BCs, we find that the levels of phase noise of the RF beatnote are almost similar. However, the efficiency in terms of output power of our DF-VECSEL is higher for the 0.5 mm BC than for the 1 mm thick BC, as depicted in Fig. 3. Therefore, a moderate spatial separation corresponding to roughly 50% mode spatial overlap, which ensures moderate coupling between the modes, is a good trade-off to have both good robustness and efficiency of our DF-VECSEL, as well as quite good spectral purity of the optically carried RF beat signal useful for communication applications, as already obtained at 1 μm wavelength [12].

In conclusion, we obtained tunable, low noise, and high power class-A DF-VECSEL operating at 1.55 μm. An intracavity BC spatially separates the two polarization eigenstates inside the active medium, and hence ensures simultaneous and robust oscillation of two modes of different frequencies. Dual-frequency oscillation at 1.55 μm
is achieved for two different coupling strengths between the lasing modes, using intracavity BC of two different thicknesses. This suggests that a 50% mode overlap is a good trade-off for robust and high power dual-frequency oscillation. The RF beat signal obtained by mixing of two optical frequencies is also obtained in both cases. The laser exhibits RO-free class-A dynamical behavior, thus minimizing excess electrical phase noise at RO frequencies. Also, the achieved optical power levels (50 mW in each mode) is large enough to allow this laser to be used in an optoelectronic oscillator without the need for RF amplifiers. The phase noise spectra of the RF beatnote for two coupling situations are also measured. This phase noise is responsible for the few megahertz wide noise pedestal for the RF signal with a few kilohertz bandwidth. Further investigations will be conducted to clarify the origins of the remaining noise, and obtain a better phase stability required in many applications. The next step will be to reduce the RF beatnote phase noise by locking it to an external low-noise RF synthesizer using a phase-locked loop (PLL) acting on an electro-optic crystal inserted inside the cavity [13].

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