Experimental demonstration of a tunable dual-frequency semiconductor laser free of relaxation oscillations

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Tunable dual-frequency oscillation is demonstrated in a vertical external-cavity surface-emitting laser. Simultaneous and robust oscillation of the two orthogonally polarized eigenstates is achieved by reducing their overlap in the optical active medium. The class-A dynamics of this laser, free of relaxation oscillations, enables one to suppress the electrical phase noise in excess that is usually observed in the vicinity of the beat note. © 2009 Optical Society of America

The generation of tunable optically carried millimeter waves is mandatory for metrology, remote sensing, and communications applications [1], such as long-range transmission of rf high-purity references [2] and wideband radar signal processing [3]. A straightforward technique to achieve optically carried rf signals is the optical mixing of two independent lasers [4]. Unfortunately, the relatively large linewidth produced by this technique requires high-performance frequency-stabilization schemes to obtain a satisfactory beat note [5]. An interesting approach can offer both narrow linewidth and continuous-frequency tunability. It is based on a single-laser cavity sustaining the oscillation of two orthogonally polarized modes whose optical frequencies can be adjusted independently [6]. This approach provides two beams sharing correlated fluctuations in the same laser cavity. Consequently, an inherent high-purity beat note of about 10 kHz width can be obtained in the free-running condition. The beat-note linewidth can even reach few hundreds of microhertz when a phase-lock loop is implemented [7]. Furthermore, the frequency difference, which is proportional to the intracavity phase anisotropy, is potentially adjustable from few tens of megahertz up to few terahertz [8].

To date, such tunable dual-frequency oscillation has been demonstrated in diode-pumped solid-state lasers, e.g., in Nd:YAG [9], Yb:Er:Glass [6], and Yb:KGW [8] lasers. The main drawback in using solid-state lasers is the presence of the well known relaxation oscillations (ROs), which are inherent to class-B operation [10]. This mechanism causes a significant degradation of the beat-note spectral purity, in particular, at the RO frequency [2]. To overcome the RO shortcomings, we have recently demonstrated that a single-mode semiconductor (SC) laser can be operated in the RO-free class-A regime [11]. This situation is reached when the photon lifetime inside the cavity exceeds the carrier lifetime within the active medium and leads to a shot-noise-limited oscillation. From a practical point of view, the class-A regime can easily be obtained by building a high-finesse vertical external-cavity Surface-Emitting Laser (VECSEL) whose cavity length is in the centimeter range [12].

In this Letter, we propose to combine the two concepts, namely, single-cavity dual-frequency operation and class-A operation, in order to obtain a tunable dual-frequency laser whose noise is inherently low.

Let us consider the experimental set up depicted in Fig. 1. The half VECSEL gain chip, operating at 1 μm, is grown by metal–organic chemical vapor deposition. It comprises a 99.99% reflecting multilayer mirror with a resonant period gain structure consisting of five InGaAs/GaAs quantum wells. The gain chip is pressed onto a cooled copper heat sink, as shown in Fig. 1. The gain-medium temperature is kept at 10°C using a Peltier module. The pump system...
The laser beam waist is 70 μm into the laser cavity (See Fig. 1). A concave dielectric mirror with a radius of curvature of 50 mm and a reflectivity of 99.5% at λ = 1 μm is placed at 45 mm away from the active medium and acts as the output mirror. In these conditions, the laser beam waist is equal to 70 μm.

The simultaneous oscillation of two orthogonally polarized states is ruled by the strength of the nonlinear coupling between the two eigenstates in the active medium [13]. Whether the coupling constant C is higher or lower than 1 leads respectively to two distinct regimes, namely, bistability or simultaneity. In [14], the reported coupling constant, in a semiconductor device, is measured to be 0.8, which is not weak enough to guarantee a robust two-polarization oscillation. Furthermore, in the peculiar case of VCSELs, different physical effects such as mechanical stress, built-in strain, thermal effects, electro-optic and elasto-optic effects in the Bragg mirrors or spin-flip dynamics can induce a significant gain dichroism, leading to polarization switching or favoring the oscillation of one particular polarization [15]. A possible way to obtain the simultaneous oscillation of the two polarizations is to control the optical losses of each polarization state with an external cavity configuration [14,16,17]. We have opted for another approach that consists in producing a partial spatial separation of the two polarization modes inside the cavity. This separation of the two polarization modes is at frequencies 15 mm away from the laser eigenstates. It is then possible to fully and independently characterize its phase and amplitude fluctuations. It is found that the amplitude noise is negligible as compared with the phase noise. A typical phase-noise spectrum is obtained using a high-speed oscilloscope. Finally, a fast Fourier transform over a duration of 0.5 s allows us to record the spectrogram reported in Fig. 3(a). This spectrogram is obtained for a beat-note frequency of 7.99 GHz, outside of the tuning range mentioned above. This situation occurs when the laser sustains the oscillation of cross-polarized eigenstates on axial modes of different orders. The obtained spectrogram enables one to identify the origin of the jitter that is found to be induced by the second harmonic of the spurious 50 Hz frequency (i.e., 100 Hz) coming from the electrical-current driver of the pump diode. In Fig. 3(b), we present a single-shot spectrum extracted from this spectrogram. The FWHM of the beat note is shown to be less than 4 kHz, which is comparable with the results usually obtained with free-running, dual-frequency, solid-state lasers.

By applying a Hamming filter to the recorded samples, we end up with the analytic form of the signal. It is then possible to fully and independently characterize its phase and amplitude fluctuations. It is found that the amplitude noise is negligible as compared with the phase noise. A typical phase-noise spectrum, obtained for a beat-note frequency equal to 7.99 GHz, is shown in Fig. 4.

Let's mention that these spectra are obtained without any insulation of the laser from the environment.
tal perturbations or any stabilization loop. In Fig. 4, one can, first, identify the electrical power supply noise at harmonics of 50 Hz. Moreover, one observes a $1/f^2$ slope for offset frequencies ranging from 1 kHz to 1 MHz, corresponding to the presence of a white frequency noise. The noise in excess appearing below 1 kHz is attributed to technical noises. Finally, it is seen that the phase-noise spectrum does not exhibit the huge noise usually observed in solid-state lasers at the RO frequency (see, for instance, [2]). This targeted behavior, which has been made possible by operating the laser in the class-A regime, is a significant improvement in the conception of low-noise, dual frequency lasers.

In conclusion, tunable dual-frequency oscillation is demonstrated in a free-ROs SC laser. This is achieved using a high-finesse VECSEL operating in the class-A regime. A slight spatial separation of the two cavity polarization eigenstates in the active medium enables the simultaneous and robust oscillation of two optical frequencies. The microwave signal, resulting from mixing the two optical frequencies, exhibits a spectral linewidth of 4 kHz. Furthermore, the beat-note frequency is continuously tunable from few megahertz up to 3.66 GHz. This laser architecture allows us to get rid of the electrical phase noise at the RO frequency, commonly observed in solid-state, dual-frequency lasers. Further analysis will be conducted to identify the origin of the remaining noise and to design a dedicated phase-lock loop in order to reach the phase stability required in stringent applications, including high-phase-purity optoelectronics clocks.

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References


Fig. 4. (Color online) Phase-noise power spectral density of the beat note at 7.99 GHz. Two independent measurements with different frequency resolutions have been superimposed to approve of the measurement technique.