Microwave Frequency Conversion Using a Coupled Cavity Surface-Emitting Laser

Chen Chen and K. D. Choquette

***Abstract*—Microwave signal mixing is observed when two signals of different frequencies are injected into the top and bottom cavities of a coupled cavity surface-emitting laser simultaneously. The signal amplitude at the mixed frequencies can be tailored by the dc bias or the microwave signal amplitude applied to the coupled optical cavities. Signal mixing enables the generation of microwave signals at new frequencies, which can be useful for optical signal processing or frequency conversion for a high-speed data link.**

***Index Terms*—Coupled cavity, semiconductor lasers, vertical-cavity surface-emitting lasers (VCSELs).**

MICROWAVE photonics has attracted considerable interest recently, as it provides promising solutions for applications such as broadband radio-over-fiber and wireless data link, ultrafast signal processing, arbitrary waveform generation, etc. [1]. With the growth of microwave photonics, many optoelectronic devices have been developed for the generation, processing, and detection of microwave signals with superior energy efficiency and signal fidelity. The vertical-cavity surface-emitting laser (VCSEL) is widely used for short- to midhaul optical communication, because of its high-speed modulation, low-cost manufacturability, and high reliability [2]. The analog performance of the VCSEL has been studied for different microwave applications [3]–[7].

In this letter, we show that a VCSEL with an optically coupled cavity structure, also known as the composite-resonator vertical-cavity laser (CRVCL), has a unique ability for signal mixing, and thus can generate microwave signals at new frequencies. Specifically, when two microwave signals of different frequencies are each injected into one of the coupled cavities, the longitudinal optical mode of the CRVCL is modulated by these two microwave frequencies simultaneously. The beating between the microwave frequencies produces signal mixing, which can be observed from the frequency spectrum of the optical signal. Additionally, the CRVCL has the ability to engineer the signal amplitude of the mixed frequencies by varying the dc bias or the microwave signal amplitude applied to the CRVCL. This functionality can enable new device applications of the CRVCL for optical signal generation and frequency conversion.

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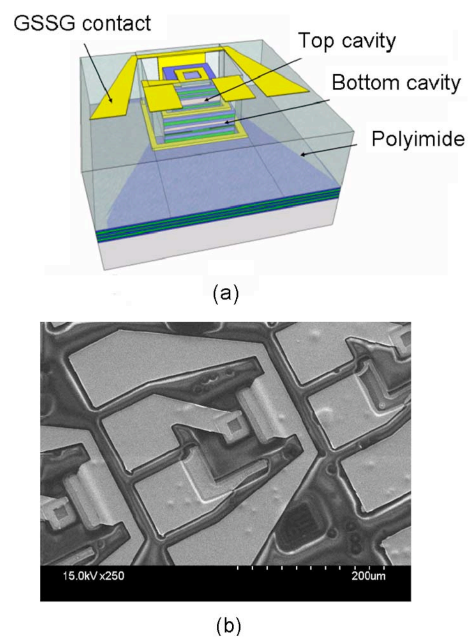

Fig. 1. (a) Schematic of a CRVCL with a GSSG coplanar contact on the planarized surface. (b) SEM of a fabricated CRVCL with a GSSG contact.

Fig. 1(a) illustrates the device structure of the CRVCL studied in this letter. The CRVCL is fabricated from an epitaxial wafer that consists of a monolithic bottom p-type distributed Bragg reflector (DBR) with 35 periods, a middle n-type DBR with 12.5 periods, and an upper p-type DBR with 22 periods. The middle DBR mirror separates two optical cavities, each of which contains five GaAs–$Al_{0.2}Ga_{0.8}As$ quantum wells nominally lasing at 850 nm. An 11×11 μm^2 ion implantation aperture and a 5×5 μm^2 oxide aperture are formed in the top and bottom mesas, respectively, to confine charge carriers. Ohmic contacts are deposited to create electrodes in the top, middle, and bottom DBR mirrors. A ground-signal-signal-ground (GSSG) coplanar contact is used to facilitate the high speed signaling to both optical cavities. The SEM image of a resulting device is shown in Fig. 1(b).

Fig. 2 shows the light versus current (*L*–*I*) characteristics of the CRVCL at room temperature. The top cavity current is varied for different dc current into the bottom cavity. The light output increases and the threshold current decreases as a larger bottom cavity current produces higher laser gain [8], [9]. The kinks in the *L*–*I* curves indicate the lasing transition from the shorter to the longer wavelength longitudinal mode, which arise from the two optically coupled cavities [8]. The presence of the kinks increases the nonlinearity of the CRVCL,

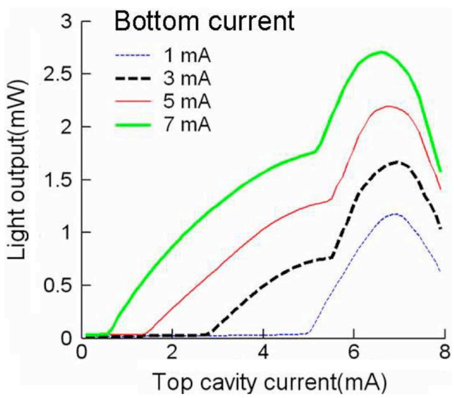

Fig. 2. Light output versus top cavity current with different dc current in the bottom cavity.

which is exploited in this letter. For this particular CRVCL, lasing at several transverse modes is also observed for each of the two longitudinal modes. The RF signals are not found to preferentially couple to either longitudinal mode.

The microwave optical signal mixing can be observed using a broadband RF spectrum analyzer. The light output from the CRVCL is collected in a cleaved 62.5-μm core graded-index multimode fiber, and then detected with a high-speed photodetector that is connected to the RF spectrum analyzer. Fig. 3 illustrates the RF spectra of the CRVCL output under different conditions of microwave signal injection, when the dc current in the top and bottom cavities is 3 and 5 mA, respectively. Microwave signals at the frequency $f_1 = 3$ GHz and $f_2 = 3.2$ GHz from two individual RF signal generators are injected into the top and bottom cavities of the CRVCL, respectively. The injected RF power is 0 dBm for both microwave signals. The resolution bandwidth of the RF spectrum analyzer is 1 MHz. The envelope of the noise floor is dictated by the laser noise spectrum. Fig. 3(a) and (b) illustrates the RF spectrum from the CRVCL when only the top or bottom cavity is directly modulated, respectively. With f_1 and f_2 indicating the fundamental frequencies, the second harmonics ($2f_1 = 6$ GHz and $2f_2 = 6.4$ GHz) and third harmonics ($3f_1 = 9$ GHz and $3f_2 = 9.6$ GHz) can also be observed due to the large RF power of the injected microwave signals. Note that all the harmonics are generated within the CRVCL. Fig. 3(c) illustrates the RF spectrum of the CRVCL output when both cavities are modulated simultaneously by the microwave signals. As a result, signal mixing up to the fifth-order terms are observed, producing the mixed frequencies at $f_2 - f_1 = 0.2$ GHz, $2f_1 - f_2 = 2.8$ GHz, $2f_1 - f_2 = 3.4$ GHz, $3f_1 - f_2 = 5.8$ GHz, $f_1 + f_2 = 6.2$ GHz, $3f_1 - f_2 = 6.4$ GHz, $4f_1 - f_2 = 8.8$ GHz, $2f_1 + f_2 = 9.2$ GHz , $f_1 + 2f_2 = 9.4$ GHz, and $4f_2 - f_1 = 9.6$ GHz. It is known that the amplitude of nonlinear terms increases with the input RF power applied to a microwave device [10]. Hence, a higher order nonlinear term and/or a higher mixed frequency can be attained by increasing the RF signal power injected to the CRVCL.

Fig. 4 illustrates the RF spectra of the CRVCL output with the top cavity currents of 3, 5, and 7 mA when the bottom cavity current is fixed at 5 mA. The same input microwave signals are used as in Fig. 3. The higher order signal mixing decreases as the top current increases from 3 to 7 mA. The greatest signal mixing

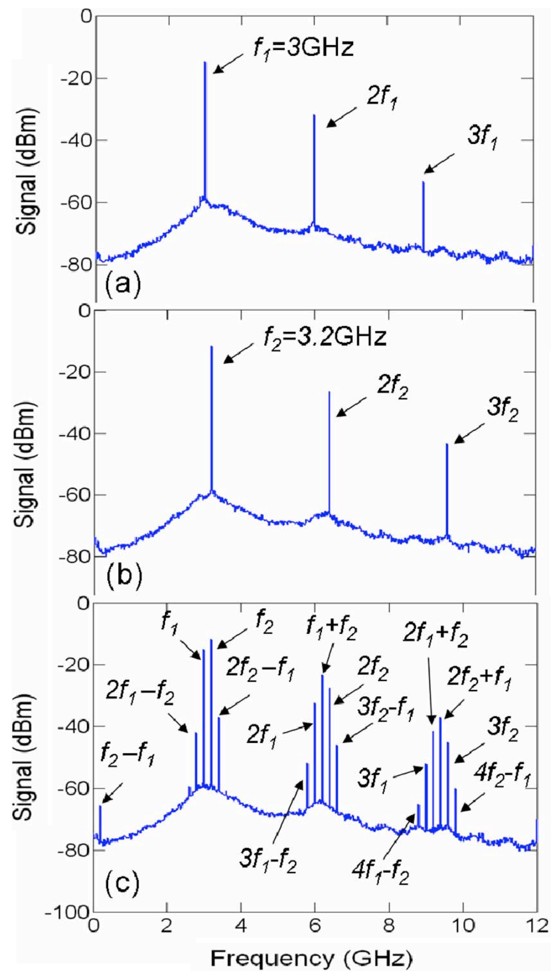

Fig. 3. RF spectrum of the CRVCL light output when only the (a) top or (b) bottom cavity is directly modulated, and (c) both cavities are modulated simultaneously.

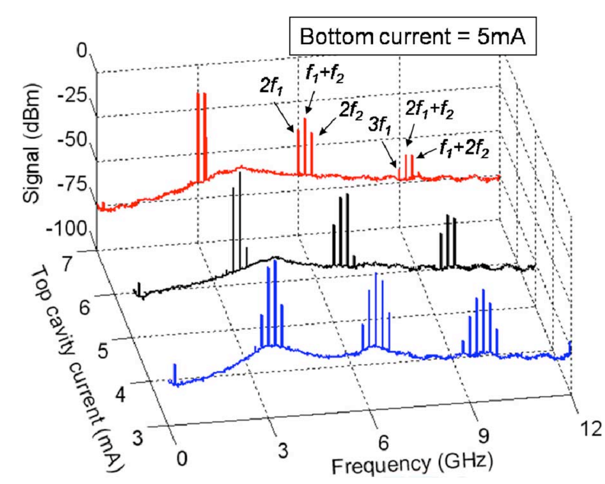

Fig. 4. RF spectra of the CRVCL light output as a function of the top cavity current with bottom cavity current held constant.

occurs at the top cavity current of 3 mA, due to the strong nonlinearity from the intrinsic distortion, when the injected RF signals are near the relaxation oscillation (RO) frequency [6]. Note that the laser noise spectrum is approximately the same as the envelope of the noise floor in the RF spectrum shown in Fig. 4,

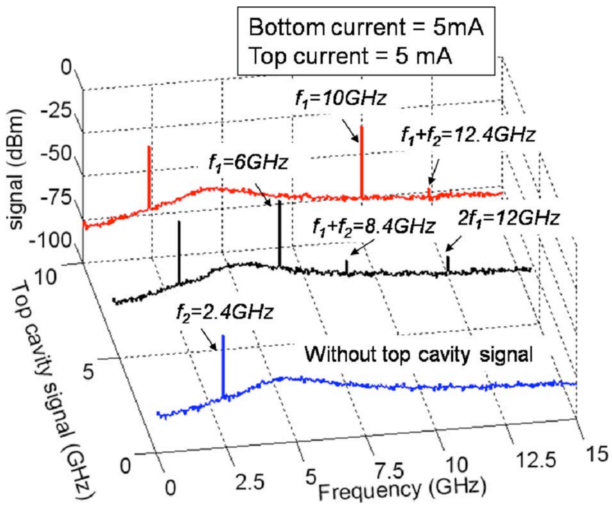

Fig. 5. RF spectra of the CRVCL light output as a function of the frequency of the microwave signal injected into the top cavity, given a fixed microwave signal in the bottom cavity.

where the peak in the laser noise spectrum indicates the RO frequency. For example, the RO frequency is approximately 3 GHz when the top cavity current is 3 mA. Although the higher order harmonics and mixed terms are suppressed when the CRVCL operates from below to above the kink in Fig. 2, the differences between the RF spectra are primarily due to the influence of the RO frequency. Moreover, the higher order harmonics as well as the mixed terms of f_1 and f_2 vary differently with increasing top cavity current. For example, the amplitudes of the mixed terms $3f_1 - f_2$ and $3f_2 - f_1$ are different when the top cavity current is 3 mA. This is because the coupled cavities tend to have asymmetric cavity conditions (arising from different current aperture sizes, modal gains, longitudinal mode distribution, etc.), which change with varying current injection, and thus, the CRVCL exhibits different linearities and modulation responses from modulating the top or bottom cavity [11].

Fig. 5 illustrates the RF spectra of the CRVCL output by varying the frequency of the microwave signal applied to the top cavity f_1, when the signal injected into the bottom cavity is fixed at the frequency $f_2 = 2.4$ GHz with a RF power of -25 dB·m. Note that the RF input power is kept small to eliminate the higher order harmonics and the potential in-band intermodulation terms from signal mixing [10]. Only one signal peak at 2.4 GHz is present in the RF spectrum if no signal is applied to the top cavity. The mixed signal at $f_1 + f_2 = 8.4$ GHz (or 12.4 GHz) is observed when the signal $f_1 = 6$ GHz (or 10 GHz) with -3 dB·m (or 20 dB·m) RF power is injected into the top cavity. The amplitude of the converted signal increases with the RF power injected into the top cavity. For $f_1 = 10$ GHz, a large RF power is injected to compensate for the decayed modulation response at frequencies higher than the RO frequency, so that the mixed signal at $f_1 + f_1 = 12.4$ GHz can be observed 4 dB above the noise floor. It is apparent from Fig. 5 that the CRVCL enables the frequency conversion from f_2 to $f_1 + f_2$, and the converted frequency is a function of the microwave frequency injected into the top cavity. The frequency mixing functionality of the CRVCL would enable a similar transmission experiment as in [3] in a compact manner without the need of an electrical mixer.

In summary, signal mixing is observed in a CRVCL when two microwave signals of different frequencies are injected into the coupled cavities. The signal amplitude at the mixed frequencies can be tailored by varying the dc bias, as both the RO frequency and the cavity asymmetry are a function of dc current injection. The mixed signal amplitude can also be tailored by varying the RF signal amplitude applied to the CRVCL, as the device nonlinearity increases with the input RF power. Finally, signal mixing can produce RF signals at new frequencies, which can be useful for signal processing and frequency conversion in the future optical data links.

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