Tunable Millimeter-Wave Generation with Subharmonic Injection Locking in Two-Section Strongly Gain-Coupled DFB Lasers

Jin Hong and Rongqing Hui

***Abstract*—Using two-section dual-mode strongly gain-coupled (SGC) distributed feedback (DFB) lasers, tunable millimeter-wave (mm-wave) generation from 18 to 40 GHz can be achieved under CW bias conditions. Due to its high speed and excellent dynamic single-mode yield in SGC DFB lasers, each section can be individually modulated to beyond 10 GHz. Using subharmonic injection locking, the linewidth of the generated mm-wave can be significantly reduced and is found to be less than 30 Hz which is limited by the stability of the microwave source and the resolution of the spectrum analyzer. This device provides a useful source to high-bit-rate optical systems and/or high-frequency wireless communications.**

***Index Terms*—Distributed feedback lasers, dual-wavelength operation, quantum wells, strongly gain-coupled DFB lasers, tunable millimeter wave source, wireless communications.**

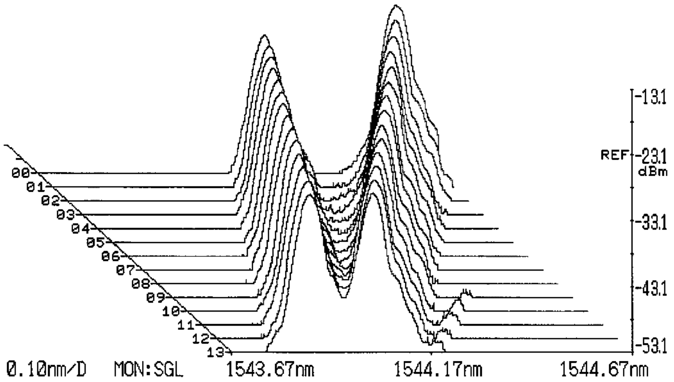

Fig. 1. Three-dimensional dual-mode optical spectrum obtained from a two-section strongly gain-coupled DFB laser, when the front section was biased at 35 mA and the rear section was tuned from 70 to 90 mA.

I. INTRODUCTION

HIGH-QUALITY continuous tunable millimeter-wave (mm-wave) generation in the range of 15–40 GHz or beyond from compact semiconductor lasers has potential applications, such as dense wavelength division multiplexing, optical short pulse generation, and high-speed wireless applications. To generate the mm-wave, a dual-wavelength source is required for the beating of two modes. Most dual-wavelength semiconductor lasers use physically separated gain sections [1], [2]. A dual-wavelength semiconductor laser in which the gain medium is shared by the two wavelengths has been demonstrated [3], [4]. The common gain medium and the shared optical output path simplify the fabrication and packaging. However, due to the strong gain competition in shared-gain media, special care has to be taken to maintain the delicate balance between gain and loss—a difficult challenge for practical system applications. In order to have both a large sidemode suppression ratio (SMSR) and a simple system-level control scheme, multiple-wavelength lasers based on a distributed feedback (DFB) structure offer a distinct advantage in these applications from the single-mode perspective.

Standard index-coupled DFB lasers can lase on either side of the stopband, depending on the (usually random) facet phases. To break this degeneracy of the two Bragg modes, a gain-coupling (GC) mechanism has been introduced into DFB laser structures by etching into active quantum wells (QW's) [5], [6]. DFB lasers with a strong gain-coupling (SGC) structure [7]–[10] were reported recently and it was demonstrated that the lasers lase predominantly on the longer wavelength side of the stopband (right Bragg mode), regardless of the random facet phases. The SGC DFB lasers are therefore suited for integration with other devices.

We report a two-section, uniform-grating, SGC DFB laser that has an excellent yield in obtaining simultaneous operation of two distinct and yet tunable wavelengths by CW bias of the two sections. The emission at each wavelength behaves, to certain extent, similarly to the emission from a single-section SGC DFB laser, except for the existence of mode beating when the two modes have similar amplitudes.

II. EXPERIMENT

The laser is a two-section 760-μm-long ridge-waveguide DFB laser with a uniform grating. The sections are separated by isolation trenches several micrometers wide, which were formed by etching through the ridges and also the active region between two sections, so that each can be biased independently, without significant current leakage. The active region of the laser has six QW's with 1% compressive strain. The grating penetrates four to five of the six QW's to form strong in-phase gain coupling [7]–[10]. The active region has an asymmetric p-side and n-side separate optical confinement layered structure to maximize the gain coupling [7]–[10]. Both the front and rear facets of the laser are antireflection-coated (around 0.5%). In the normal operating regime ($I > 2I_{\rm th}$), the relative intensity

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J. Hong is with Nortel Networks Corporation, Station C, Ottawa K1Y 4H7, Canada.

R. Hui is with the Information and Telecommunications Technology Center, Department of Electrical Engineering and Computer Science, University of Kansas, Lawrence, KS 66045 USA.

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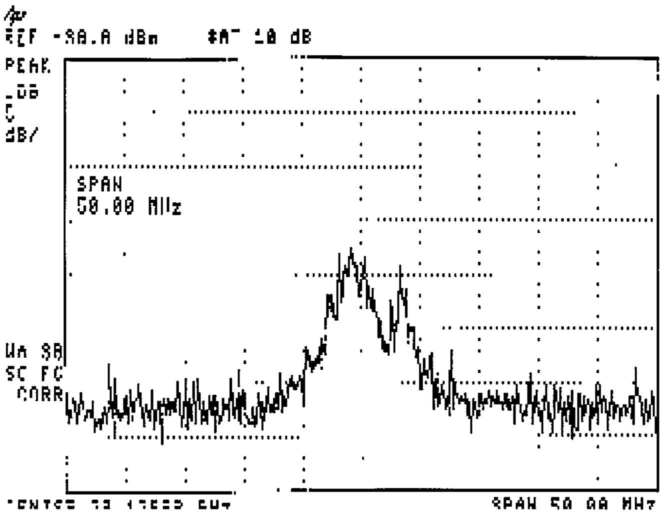

Fig. 2. The electrical beating spectrum around 20 GHz in the absence of subharmonic injection locking, for the same device shown in Fig. 1. Horizontal 50 MHz/Div. and vertical 5 dB/Div.

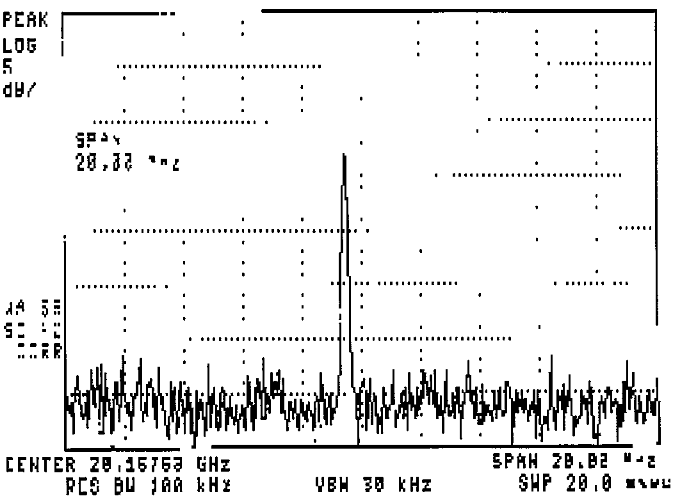

Fig. 3. The 20-GHz signal optically injection-locked by the fourth harmonic of a 5 GHz modulation. The FWHM linewidth is approximately 30 Hz (limited by the resolution of the spectrum analyzer). Horizontal 20 MHz/Div. and vertical 5 dB/Div.

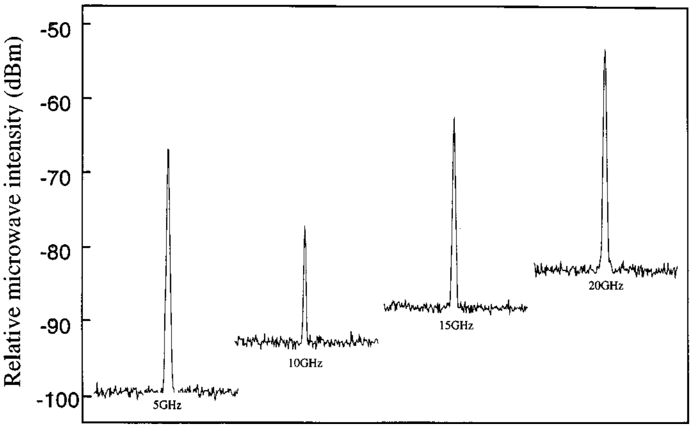

Fig. 4. The composite electrical spectrum up to 20 GHz showing both the fundamental frequency and harmonics.

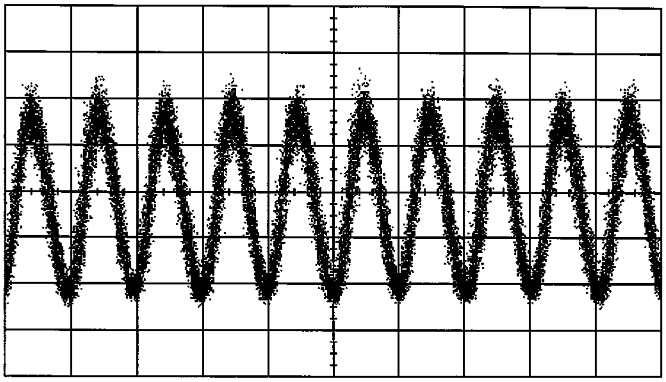

Fig. 5. The time-domain waveform with the fourth harmonic injection locking. Horizontal 50 ps/Div.

noise of the laser output is below 110 dB/Hz and the damped relaxation oscillation frequency is approximately 15 GHz. The laser is mounted on a high-speed co-planar carrier to allow for the high-speed subharmonic modulation and injection locking.

Dual-wavelength operation was obtained by biasing the two laser sections well above their respective threshold currents (∼25 mA). Fig. 1 shows a three-dimensional (3-D) plot of the optical spectrum of dual-wavelength operation, where the front section was biased at 35 mA and the rear section was tuned from 70 to 91 mA in 14 equal steps (1.5-mA/step). As a result, the frequency spacing between the two laser modes was varied continuously from about 18 to 40 GHz. Sending this dual-mode lightwave into a high-speed photodiode, the free-running electrical spectrum of the beating signal centered at approximately 20 GHz was obtained as shown in Fig. 2. Since no special effort was made on temperature control and optical isolation, the beating frequency was not stable. The linewidth was in the range of several megahertz. When a 5-GHz RF signal with a power of +9 dBm was used to modulate the rear laser section, the 20-GHz beating signal was optically injection locked by the fourth harmonic of the modulation. As shown in Fig. 3, the beating frequency was stabilized by the injection locking and the linewidth was measured to be less than 30 Hz, which was limited by the stability of the microwave source used and the resolution of the spectrum analyzer. The composite electrical spectrum is shown in Fig. 4, where both the fundamental frequency and the harmonics are shown. Since no special attention has been paid to the optical coupling efficiency and optical loss in the measurement system was not calibrated, Fig. 4 only shows the relative comparison of different frequency components. It is noted that the fourth harmonic of the signal is the strongest, which indicates that the injection locking is very efficient. This is an interesting feature of this device. Since the injection-locked harmonic at the optical beating frequency is much stronger than the fundamental, a special microwave filter may not be required in order to use the locked frequency. In order to verify this point, the time-domain waveform was also measured as shown in Fig. 5. Apart from the thermal noise of photodetection, it is noted that the time-domain response is close to a perfect sinusoidal function, which is stable with little amplitude modulation. This indicates that both the phase noise and time jitter have been significantly reduced, which is important for high bit-rate optical systems.

III. CONCLUSION

We report tunable mm-wave generation from a two-section, uniform-grating, strongly-gain-coupled DFB laser. Subharmonic optical injection locking is used to reduce the linewidth of the mm-wave to less than 30 Hz with $+9$ dBm RF power. The beating frequency can be tuned from 18 to 40 GHz continuously by varying the bias current. The excellent stability and high yield of SGC DFB lasers makes them suitable for a wide range of applications where a low-cost and high-quality mm-wave source is required for both high-bit-rate optical systems and high-speed wireless communications.

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