Rapidly Tunable Millimeter-Wave Optical Transmitter for Lidar–Radar

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***Abstract*—This paper reports on the optical generation of a rapidly tunable millimeter-wave subcarrier for lidar–radar. The millimeter-wave signal is generated by beating the output from two $Nd:YVO_4/MgO:LiNbO_3$ electrooptical monomode microchip laser sections realized monolithically in a single composite crystal. The device has a continuous tuning range up to 45 GHz. The measured chirp rate is 3816 THz/s, the voltage sensitivity is 10.6 MHz/V, and the measured residual phase noise is −106 dBc/Hz at 10-kHz offset.**

***Index Terms*—Electrooptic modulation, fiber radio, frequency-chirped lidar–radar, microchip laser, optical heterodyning.**

I. Introduction

INCREASINGLY, microwave and millimeter-wave techniques are adapted to optical systems, such as lidar for detection of underwater objects, aerial turbulence, and tumors in human tissues [1], [2]. Microwaves and millimeter waves do not penetrate water or tissue, but light at specified wavelengths does and, therefore, lidar has been used for detection of objects submerged in water or embedded in tissue. However, these media intensely scatter light resulting in poor contrast and target identification. Light modulated at microwave frequencies, i.e., lidar–radar, has superior performance compared to lidar, as was demonstrated by Mullen *et al.* [1]. In this approach, the lidar–radar echo is detected, and the microwave envelope recovered and subjected to conventional coherent radar signal processing. This paper concerns the development of a novel rapidly tunable microchip laser for sophisticated frequency chirped lidar–radar technique. To obtain an accurate determination of the depth D and size R of the target, i.e., chirped lidar radar, where the millimeter-wave modulation frequency is tuned, is considered.

The beat frequency Δf of a chirped detection scheme is

$$\Delta f = \frac{dF}{dt}\tau = \frac{dF}{dt}\cdot\frac{2D}{u}$$

where dF/dt is the chirp rate, τ is the round-trip delay, and u is the velocity in the medium. Medical applications call for the most stringent requirements on the chirped system since the depth of a typical target (tumor) is extremely short (∼2.5 cm), and the round-trip time τ is of the order of 250 ps. To achieve better signal-to-noise ratio at the lidar–radar receiver, Δf is desired to be in the megahertz range, which implies chirp rates in excess of 1000 THz/s.

Furthermore, the small size of the tumor (∼3 cm) necessitates a high resolution $\Delta R = u/2\Delta F$, which entails a frequency excursion ΔF of about 30 GHz. While medical applications pose the most stringent requirements, other applications also require rapidly tunable sources [3]. The subsequent sections describe the design, fabrication, and testing of an optical transmitter that is capable of generating the chirp rate and frequency excursion defined above.

The following four methods of optical generation of a millimeter-wave subcarrier exist:

1) direct modulation of a laser diode (LD);
2) external modulation;
3) laser mode locking;
4) heterodyning of two single-mode lasers.

Direct modulation of the LD is limited in bandwidth. External modulation is complicated, expensive, and often involves excessive optical losses. Laser mode locking is a very narrow-band process difficult to frequency modulate [4]. Laser heterodyning is a broad-band process and it can be ideal for the generation of tunable millimeter-wave subcarrier if it can be adequately stabilized [5].

LDs have very fast FM modulation speed [6]; however, due to their relatively poor spectrum quality, complicated phase-locked loop (PLL) with broad bandwidth and short delay are employed to achieve a good quality heterodyning signal in the millimeter-wave domain. Most viable optical heterodyning approaches producing high-quality millimeter-wave signals employ solid-state lasers with temperature or piezo-transducer (PZT) tuning [7]–[9], both of which result in very slow tuning speed. In this paper, a novel approach using a monolithic microchip laser with electrooptic tunability is discussed.

II. Tunable Transmitter Concept

The concept of rapidly tunable millimeter-wave optical transmitter is shown in Fig. 1. Two identical optical cavities are formed by depositing dielectric mirrors on opposite ends of a composite $Nd:YVO_4/MgO:LiNbO_3$ crystal assembly. The two side-by-side lasers are each pumped by independently driven 808-nm high-power LDs. The $Nd:YVO_4$ provides a homogenous gain medium that may lead to multimode lasing in the presence of spatial hole burning. However, the short

Manuscript received January 24, 2001; revised June 26, 2000. This work was supported in part by the Office of Naval Research under Grant N00014-00-1-0781 and under Grant N00014-97-1-1082.

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Publisher Item Identifier S 0018-9480(01)08696-3.

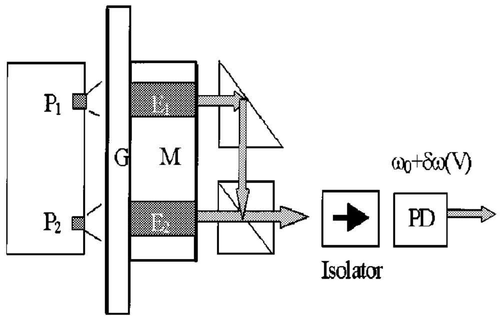

Fig. 1. Microchip laser structure. P_1 and P_2 are two independent pumps. G is the 0.3-mm-long Nd : YVO_4 gain section, M is the MgO : $LiNbO_3$ phase modulation section. E_1 and E_2 are electrodes.

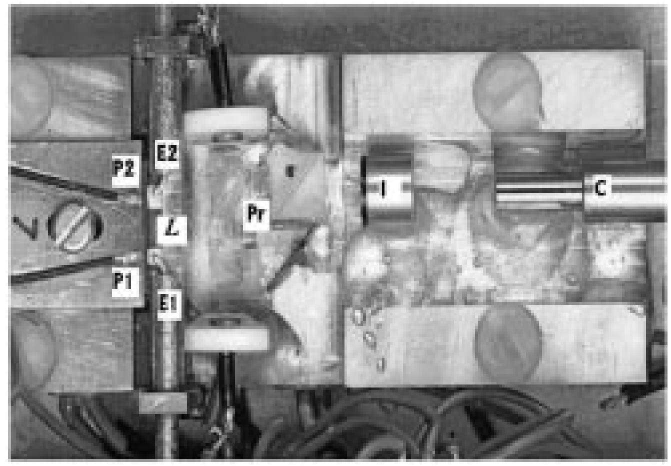

Fig. 2. Heterodyne transmitter implementation, where P_1 and P_2 are the two diode pump, L is the Laser crystal, which is composed of a 0.3-mm-long Nd : YVO_4 section and 1.2-mm-long MgO : $LiNbO_3$ section, E_1 and E_2 are the electrodes deposited on the $LiNBO_3$ modulator, Pr is the beam coupling prism, I is the isolator, and C is the fiber collimator.

pump absorption length [10] reduces the chance for spatial hole burning, thus assuring single-mode lasing. In addition, the pump beam produces a thermal lens effect in the Nd : YVO_4, resulting in only one transverse mode in the cavity. The outputs of the two lasers are combined, coupled into a single mode fiber, and transmitted to a high-speed photodiode, where the optical signals self-heterodyne, resulting in a microwave or millimeter-wave signal. The monolithic configuration gives the device simplicity, compactness, stability, and reduced sensitivity to external temperature fluctuations.

Ideally, if the two lasers are at the same temperature, pumped at the same level, and subjected to no applied voltage, their output is expected to be identical in optical frequency and intensity. However, if the output frequency of either laser is shifted by an applied voltage, or subjecting it to different temperature or pump power, then a heterodyned beat frequency is produced at the photodetector. Specifically, we can use pump power biasing to set the initial frequency ω_0 of the millimeter-wave subcarrier. By applying a time-dependent voltage to one of the lasers [e.g., $V_2(t)$], we can then generate a broad-band rapidly tunable millimeter-wave subcarrier $\omega(t) = \omega_0 + \delta\omega(t)$.

The implementation of the transmitter presented in this paper is shown in Fig. 2. This configuration consists of a 0.3-mm-long Nd : YVO_4 crystal (the gain medium) and a 1.2-mm-long MgO : $LiNbO_3$ crystal (the tuning section). The laser has a 160-mW threshold and a slope efficiency of better than 30% [11]. Electrodes are deposited on the top and bottom of the 1 mm thick MgO : $LiNbO_3$ section for the tuning/modulation input signals.

Important considerations regarding the performance of this optical transmitter include the tuning range, speed, and sensitivity to pump power, temperature, and voltage variations. Another important consideration is the quality of the millimeter-wave signal, particularly phase noise, which limits the optical transmitter dynamic range. These issues are addressed in the following sections.

III. Tuning Range, Sensitivity, and Speed

For rapid chirping of the optical transmitter, a time-varying voltage is applied to one of the lasers, causing a shift in the heterodyned millimeter-wave frequency. Principal concerns are the achievable tuning range, sensitivity, and speed.

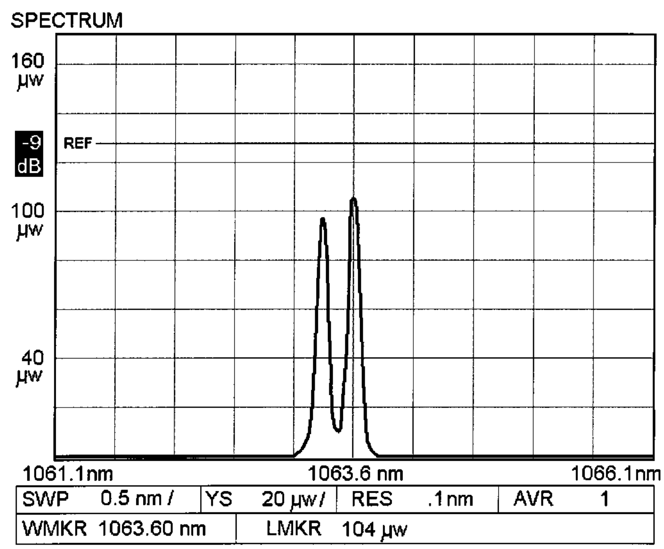

Fig. 3. Optical spectrum of the heterodyne signal ($T = 25$ °C, $\mathrm{pump}\ 1 = 250$ mW, $\mathrm{pump}\ 2 = 300$ mW). The 0.3-nm wavelength separation between the outputs of two microchip-lasers corresponds to 90-GHz heterodyne signal.

A. Transmitter Tuning Range

Two types of tuning ranges are identified: the overall tuning range (OTR) and continuous tuning range (CTR). The OTR is the maximum frequency excursion over which single-mode operation is maintained. The CTR is the maximum frequency excursion over which the transmitter can be varied without mode hoping. In general, the OTR will be larger than the CTR. The CTR determines the transmitter performance in applications like frequency-chirped lidar–radar where a continuous relationship between the input signal and millimeter-wave frequency is desired.

1) Transmitter OTR: The OTR is basically determined by the laser gain bandwidth, which is approximately 120 GHz for Nd : YVO_4. To illustrate the setting of the transmitter bias point, refer to Fig. 3. This figure shows the optical spectrum of the two lasers when they are set to two different bias points ($P_1 =$

250 mW, $P_2 = 300$ mW, $T = 25$ °C). The spectrum reveals a wavelength separation of 0.3 nm, which corresponds to 90-GHz millimeter-wave heterodyne frequency. Proper adjustment of pump power results in the generation of millimeter-waves up to 120 GHz.

2) Transmitter CTR: The CTR of the transmitter is determined by the CTR of a single microchip laser. The microchip laser may be continuously tuned when the following two conditions are satisfied: 1) no mode hoping occurs and 2) single-mode operation is maintained. The cavity free spectrum range (FSR) sets the upper bound for microchip laser CTR due to mode hoping, while single-mode operation limits the actual CTR at a specific pump level.

Zayhowski [10] reported a comprehensive study on the single-mode operation of microchip lasers even when adjacent modes were pumped above the conventional threshold level. He calculated the effects of spatial-hole burning and excited-state diffusion on the standing-wave laser cavities and determined the extended threshold level for single-mode operation. In our investigation, we modified his model to find the extent of single-mode operation with different biasing conditions and voltage tuning. State diffusion, which is a strong function of the laser media and environment factors, increases the tuning range. Since, in this analysis, we are interested in the lower bound of the tuning range, state diffusion will be neglected.

The condition for the laser to operate in a single-mode fashion is related to the factor $\zeta_{(0,\,i)}$, which describes the normalized necessary pump power (with respect to laser threshold) for the ith mode to start to oscillate. Thus, the single-mode condition can be expressed by the following relation [10]:

$$P_0 < \zeta_{(0,\,i)_{\min}} P_{\text{threshold}} \qquad (1)$$

where P_0 is the actual pump power, $P_{\text{threshold}}$ is the pump power at the lasing threshold, i is the cavity mode number, and $i = \ldots, -3, -2, -1, 1, 2, 3, \ldots$, and the number with "0" designating the oscillating cavity mode. The subscript "min" indicates the minimum value of $\zeta_{(0,\,i)}$. The factor $\zeta_{(0,\,i)}$ is related to the discrimination factor $\beta(0,\,i)$, which describes the competition between the oscillating and ith modes [10]. To take into consideration the laser frequency tuning, we recalculated the discrimination factor [10, eq. 9] as follows:

$$\beta_{(0,\,i)} = \frac{1 + \left[2(f_i - f_0 + \delta f)/\Delta f_{3\,\text{dB}}\right]^2}{1 + \left[2\delta f/\Delta f_{3\,\text{dB}}\right]^2} \qquad (2)$$

where f_0 and f_i are the optical frequency of the second oscillating and the ith mode, respectively, δf is the laser frequency digression from the center of the gain spectrum, and $\Delta f_{3\,\text{dB}}$ is the gain spectrum 3-dB bandwidth. The discriminator factor changes as the frequency is tuned from the gain spectrum center, which result in $\zeta_{(0,\,i)\,\min}$ variation. The maximum tuning range is reached when the actual normalized pump power becomes greater than $\zeta_{(0,\,i)\,\min}$ as the oscillating frequency is moved further away from the center of gain spectrum. By calculating the relationship between $\zeta_{(0,\,i)\,\min}$ and the frequency tuning from the gain center, we get the actual microchip laser CTR limited by the single-mode operation condition.

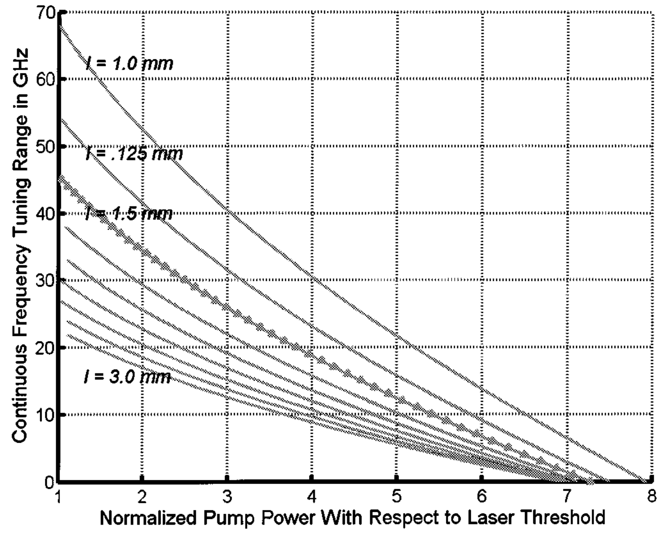

Fig. 4. Laser tuning range versus normalized pump power for different cavity lengths. The overall cavity length is varied from 1 to 3 mm, while the Nd : YVO_4 section length is held constant at 0.3 mm. The 1.5-mm-long cavity is used in the experiment.

Simulations have been performed to determine the tuning range as a function of pump intensity level for various cavity lengths. In order to determine $\zeta_{(0,\,i)\,\min}$, we calculated $\zeta(0,\,i)$ for 21 cavity modes, one at the gain center, and ten below and ten above this frequency. Due to the Lorenzian gain profile of the material, modes lying outside this span would require very high pump power levels, well exceeding the practical pump intensity levels and, therefore, are not considered. In the simulation, the length of the Nd : YVO_4 section was held constant at 0.3 mm, while the total cavity length was varied from 1.0 to 3.0 mm in 0.25-mm increments. The tuning range is a strong function of pump power, as shown in Fig. 4. At the threshold pump level, the transmitter can be tuned continuously over the FSR, which represents the upper bound of the CTR. The tuning range decreases as the pump level increases. For the specific microchip laser considered here with a cavity length of 1.5 mm, the maximum CTR is 45 GHz. As the normalized pump intensity increases to 7.4, the tuning range vanishes. It should be noted that the selection of 1.5-mm cavity length is a compromise between the CTR and voltage tuning sensitivity. Voltage tuning sensitivity will be discussed in the following section.

B. Heterodyne Transmitter Tuning Sensitivity

In this section, we discuss the tuning sensitivity of the optical transmitter with respect to voltage, pump power, and temperature. These parameters are important in understanding how to efficiently bias and tune the transmitter.

1) Electrical Voltage Tuning Sensitivity: When voltage is applied across the $LiNbO_3$ section of one microchip laser, the effective cavity length and, thus, resonant optical frequency, changes as well. At the photo detector, the heterodyne frequency is then changed by

$$\delta f = \frac{\eta}{2 \cdot d}\, n_1^2 r_{33} \cdot f_{\text{optical}} \cdot \frac{n_1 l_1}{n_1 l_1 + n_2 l_2}\, \delta V \qquad (3)$$

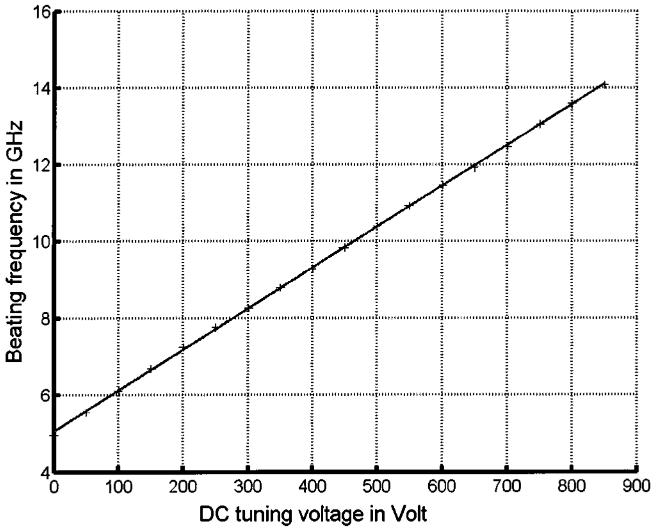

Fig. 5. Voltage tuning sensitivity. The measured slope is 10.6 MHz/V.

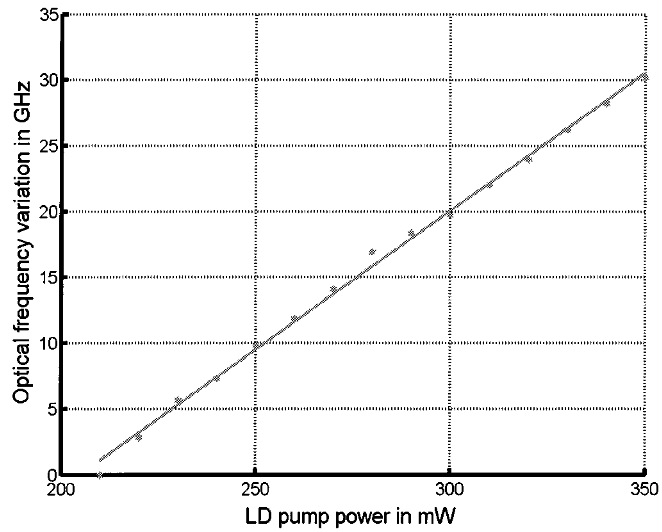

Fig. 6. Optical frequency variation versus pump power. The measured sensitivity is 210 MHz/mW.

where n_1 is the refractive index of extraordinary wave in the $LiNbO_3$ section, n_2 is the refractive index of a π polarized wave in the $Nd:YVO_4$ gain section, l_1 is the electrooptic section ($LiNbO_3$) length, l_2 is the gain section ($Nd:YVO_4$) length, d is the thickness of the $LiNbO_3$ section, r_{33} is the $LiNbO_3$ electrooptic coefficient along the z-axis, $f_{\rm optical}$ is the optical frequency, and η is the overlap efficiency between the applied electric field and laser cavity mode. Specifically, for our tunable microchip laser, the calculated tuning sensitivity is 13.4-MHz/V with an estimated 80% overlap efficiency.

The voltage tuning sensitivity of the transmitter was characterized by measuring the heterodyne signal frequency in the microwave domain versus the applied voltage. Varying the voltage from 0 to 850 V, we measured a 10-GHz beat frequency variation, corresponding to a measured tuning sensitivity of 10.6 MHz/V, as shown in Fig. 5. The discrepancy between the measured and theoretical sensitivities is caused by the inadequate field overlap. Decreasing the crystal thickness from 1 to 0.15 mm, and improving the overlap efficiency, a sensitivity of 100 MHz/V can be achieved.

2) Sensitivity to Pump Power Tuning: Pump power variation will perturb the laser cavity in two ways. First, it will cause a spatially dependent localized temperature variation, which results in a refractive index change. Second, it will change the laser media inversion density and, thus, the refractive index as well. In both cases, it will modify the cavity resonance condition and, hence, the optical frequency will change.

The sensitivity to the pump power variation was experimentally determined by raising the pump power from 210 to 350 mW. The resulting 32-GHz frequency shift is shown in Fig. 6, corresponding to sensitivity of 210 MHz/mW. The heterodyne signal frequency is extremely sensitive to the pump power variations, therefore, quiet stable LD pumps are required for chirped radar applications.

3) Temperature Sensitivity: First the effect of the temperature variation on the optical frequency of a single laser is determined, and then this result is extended to the transmitter comprised of the two lasers. Specifically, the effect of temperature fluctuation on the heterodyned millimeter-wave frequency is calculated. The temperature-induced laser frequency variation is

$$\delta f_{\rm optical} = \frac{\delta n_1(T) l_1 + \delta n_2(T) l_2 + n_1 \delta l_1(T) + n_2 \delta l_2(T)}{n_1 l_1 + n_2 l_2} \cdot f_{\rm optical}. \tag{4}$$

The thermal expansion coefficient of $MgO:LiNbO_3$ and $Nd:YVO_4$ are 2.0 $\times$ 10^{-6} K^{-1} [4] and 7.2 $\times$ 10^{-6} K^{-1} [12], respectively. The temperature-induced refractive index variation coefficient is 6.7 $\times$ 10^{-5} K^{-1} [4] for $MgO:LiNbO_3$ and 3.9 $\times$ 10^{-6} K^{-1} [12] for $Nd:YVO_4$. Therefore, the estimated thermal tuning sensitivity is 18 GHz/K.

External temperature fluctuations will affect both laser sections in an identical manner, thus, the heterodyned signal sensitivity can be expressed as

$$\frac{\delta \omega}{\delta T} = \frac{\delta f_{\rm optical}}{\delta T} \cdot \frac{\omega}{f_{\rm optical}} \tag{5}$$

where ω is the heterodyne signal frequency. Equation (5) reveals that if we bias the transmitter to produce a 100-GHz beat frequency, then the temperature-induced drift is 6 MHz/K. As expected, the realization of the two laser sections in a single crystal assembly dramatically improves the temperature stability.

C. Transmitter Tuning Speed

The tuning speed of the optical transmitter is determined by the response speed of the $LiNbO_3$, driving circuitry, and laser dynamics. A rigorous study of the laser dynamics requires the introduction of a time-dependent velocity (or index of refraction) into the mathematical formulation of the microchip laser resulting in a very complex nonlinear problem, well beyond the scope of this paper. The most relevant theoretical study was carried out by Genack *et al.* [13], who studied the response of the laser in the presence of a very thin electrically tunable crystal placed against one of the mirrors in the optical cavity. Their heuristic arguments predicted a very fast response, but their derivation does not hold for our case where the tunable material covers 80% of the cavity.

The actual dynamics of the laser comprises of a series of adiabatic perturbations caused by the field-induced time-varying index of refraction (dn/dt). This has two effects within the cavity. First, it stimulates a time variation of the phase, or frequency, which is proportional to the field-induced nonlinear electrooptic effect $\delta f_{nl}(t) = a\delta E(t)$. Second, it continuously readjusts the resonance condition in the cavity $\delta f_{\mathrm{res}}(t) = b\delta E(t)$. If the modulator section is much longer than the gain section ($l_1/l_2 \gg 1$), then $a = b = (f_{\mathrm{optical}}/2)n^2 r_{33}$, and the chirp rate is determined by the response speed of the electrooptic effect in the $LiNbO_3$, which is in the range of hundreds of gigahertz and by the speed of the driving circuit.

In general, if the condition $l_1/l_2 \gg 1$ does not hold, the analysis becomes more complicated because the coefficient "a" is no longer a constant. For the laser under consideration, $l_1/l_2 = 4$ and the difference between the frequency changes remains very small. Specifically, simulations indicate that $|\delta f_{nl}(t) - \delta f_{\mathrm{res}}(t)| = \varepsilon_f \ll 1/\tau_c$, where $\tau_c = 1.1$ ns is the cold cavity lifetime. This implies that the laser dynamics does not limit the tuning speed and, once again, the chirp rate is governed by speed of the electrooptic effect or by the speed of the driving circuit.

IV. Heterodyne Transmitter Characterization

The motivation for developing a fast tunable millimeter-wave optical transmitter was to generate a frequency-chirped millimeter-wave subcarrier for hybrid lidar–radar and other applications. In these applications, low carrier phase noise is desired to achieve high dynamic range. Optical heterodyning would transfer the laser phase noise directly into the millimeter-wave subcarrier; therefore, a type-2 PLL with 1-MHz loop bandwidth and a damping factor of 0.7 [14] is employed to suppress the millimeter-wave subcarrier phase noise. The loop delay is approximately 10 ns, which is substantially less than the inverse of the loop gain bandwidth. Furthermore, due to the narrow linewidth (~kHz) of the solid-state microchip laser, the effect of the loop delay may be neglected [5]. In the characterization experiment, the transmitter is locked to an 8-GHz microwave reference carrier. Due to the heterodyning configuration, the result is equally applicable to frequency in the millimeter-wave range.

A. Chirped-Signal Generation

The chirped-signal generation and characterization is carried out using the experimental setup shown in Fig. 7. The free-running transmitter was initially set to generate a heterodyne frequency of 8 GHz by adjusting the pump power while keeping their temperatures constant.

With the transmitter stabilized, a 10-MHz 18-V peak-to-peak ramp signal, i.e., the lower trace in Fig. 8, was applied to one of the microchip lasers. A microwave homodyne frequency discriminator was used to recover the resulting frequency chirp. The recovered signal, i.e., the upper trace in Fig. 8, matches with the applied voltage ramp. A frequency excursion of 190.8 MHz over a 50-ns time period was measured, which corresponds to a chirp rate of 3816 THz/s. The available voltage ramp generator currently limits the chirp rate, but the transmitter is capable of producing higher speed chirps if required.

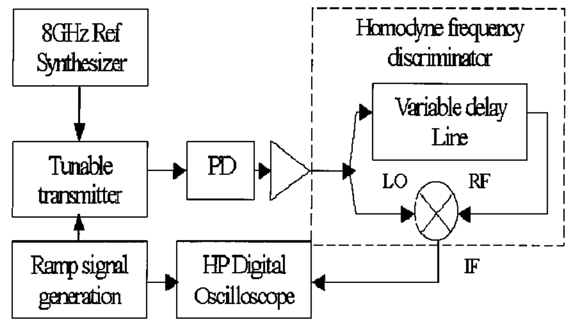

Fig. 7. Experimental setup for chirped-signal generation and characterization. The heterodyne transmitter is locked to an 8-GHz reference signal and modulated by a 10-MHz 18-V_{p-p} ramp signal.

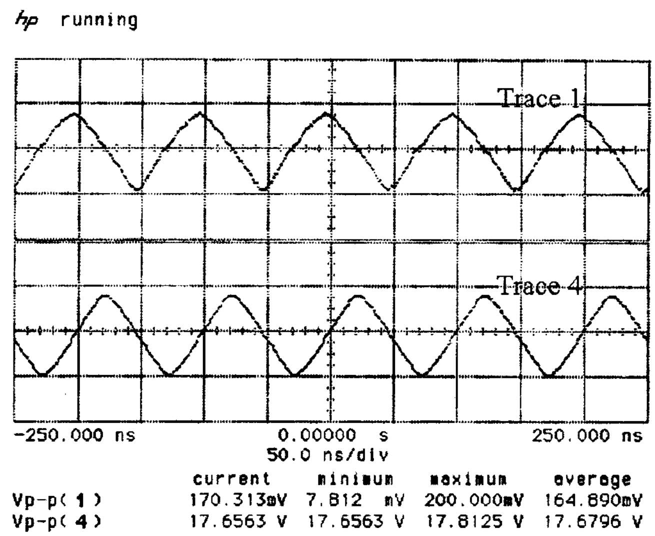

Fig. 8. Frequency chirping captured by homodyne frequency discriminator. Applied ramp signal is shown in the bottom trace and the frequency response on the top trace. The chirping rate observed is 3816 THz/s.

B. Noise Characterization

The phase noise was characterized with the transmitter set and locked to an 8-GHz bias point using the PLL. Fig. 9 shows the measured microwave spectrum and reveals an absolute single-sideband (SSB) phase noise of −90 dBc/Hz at 10-kHz offset frequency.

Since the absolute phase noise was very close to the synthesizer phase noise used in the PLL, it was necessary to find the actual contribution of the optical transmitter. Thus, the SSB residual phase noise was also measured using a phase discriminator measuring setup [15], and was found to be −106 dBc/Hz at 10-kHz offset.

By measuring the microwave spectrum of the generated heterodyning millimeter-wave signal, a preliminary characterization of the transmitter amplitude noise was accomplished. Two sets of discrete spurs at 300 and 500 kHz with amplitude peaks below −30 dBc were identified. The discrete spurs are due to the relaxation oscillation of each laser and are dependent on the pump power level. For frequencies above the relaxation

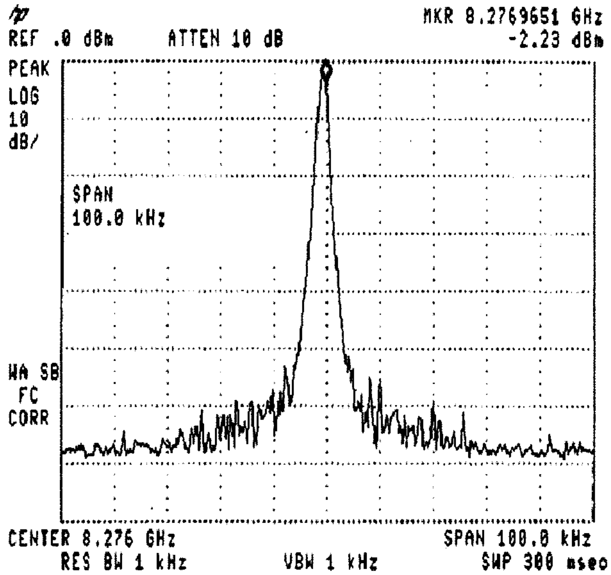

Fig. 9. Heterodyne signal spectrum with the tunable transmitter locked to a 8.277-GHz synthesizer reference signal.

oscillation, the amplitude noise decreases rapidly to levels below −150 dBc/Hz. The relaxation oscillation peak can be suppressed by employing feedback control to the pump laser. Peak suppression better than 30 dB has been reported in the literature [16].

The measured high chirping rate and low amplitude and phase noises indicate the potential of the heterodyne optical transmitter for many applications.

V. Conclusion

A tunable high-speed optical heterodyne transmitter for lidar–radar has been designed, fabricated, and characterized. The transmitter consists of two 1.5-mm-long microchip lasers co-located on the same electrooptic crystal assembly. The monolithic configuration of realizing two lasers within a single microchip crystal makes the transmitter tolerant to environmental fluctuations. The outputs of the two lasers are heterodyned to produce a millimeter-wave signal, which is electrically tunable. The max chirping rate observed is 3816 THz/s, and the residual SSB phase noise is −106 dBc/Hz at 10-kHz offset. The current device has a voltage tuning sensitivity of 10.6 MHz/V and a potential tuning range of 45 GHz.

Current efforts include increasing the voltage sensitivity to 100 MHz/V by reducing the crystal thickness and improving the electrical contacts. Furthermore, we are testing the transmitter in a lidar experiment and exploring its potential for communications as a directly modulated low-noise microchip laser source.

Acknowledgment

The authors wish to thank the useful comments of A. Rosen, Sarnoff Corporation, Princeton, NJ, F. Funk, Naval Research Laboratory (NRL), Washington, DC, B. Jemison, Electrical and Computer Engineering Department, Lafayette College, Easton, PA, and A. Daryoush, Electrical and Computer Engineering Department, Drexel University, Philadelphia, PA.

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