Optically generated dynamically tunable, low noise millimeter wave signals using microchip solid state lasers.

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Abstract — **This paper concerns the optical generation of microwave and millimeter wave signals by heterodyning two or more solid state microchip lasers. The lasers can be temperature and voltage tuned to produce beat frequencies up to 200 GHz with tuning speed of 50GHz/microsec. A novel fiberoptic delay is employed to stabilize the transmitter yielding a measured phase noise of -101 dBc/Hz at 10 kHz offset.**

I. Introduction

This paper concerns recent developments on a low noise, dynamically tunable millimeter wave transmitter employing solid-state microchip lasers and an optical signal processing scheme. Specific goals of the project are the optical generation of dynamically tunable microwave/millimeter wave signals ranging from a few GHz up to 100 GHz and beyond with phase noise below -100 dBc/Hz at 10KHz offset over the entire frequency range. Applications of the optical/millimeter wave transmitter include frequency agile spread spectrum and orthogonal frequency division multiplexed communications, advanced surveillance (lidar-radar), and medical diagnostics.

In section II we discuss the basic layout of the optical/millimeter wave transmitter and the fabrication of the microchip lasers. Alternate approaches for the frequency stabilization and phase noise suppression are discussed in section III. Discussion of the results and relation to critical applications is presented in section IV.

II. Millimeter Wave/Optical Transmitter Design and Fabrication.

The basic approach of the dynamically tunable millimeter wave/optical transmitter (DTMOT) is depicted in Fig. 1. Li, et al. [1,2] reported an earlier version of this device in the context of very fast chirp [1] and MSK communication experiments [2]. The transmitter is comprised of two subsystems: i. an array of two or more microchip lasers whose heterodyned output generates the millimeter wave signal, and ii. a stabilizing feedback mechanism.

The optical resonators are composed of three parts: the gain medium, the modulator section, and the output mirror. The gain medium in this experiments is a 0.2 mm long Nd:YVO_4 crystal with high reflectivity mirror (>99.9%) and antireflection (AR) coatings deposited at the opposite ends of the crystal. The 1.3 mm long $LiNbO_3$ tuning section has AR coatings at both ends, and electrical contacts deposited in the direction normal to the optical wave propagation. The thickness of the $LiNbO_3$ section (i.e., electrode separation) is currently 0.5 mm. The gain and tuning sections as well as the output mirror (99%) are aligned and glued to a substrate forming a microchip laser that operates in both single spatial and single longitudinal modes. The laser is placed on a thermoelectric cooler and excited on the gain side by 808 nm laser diode. By proper selection of the dielectric mirrors, the laser can operate at a wavelength of either 1.06 μm or 1.34 μm. The output beams of two or more lasers are coupled into single-mode optical fibers and fed into a high-speed photodetector where they heterodyne producing a millimeter wave beat signal. A photo of the functioning microchip module, including the pump diode and temperature cooler, is shown in Fig. 2.

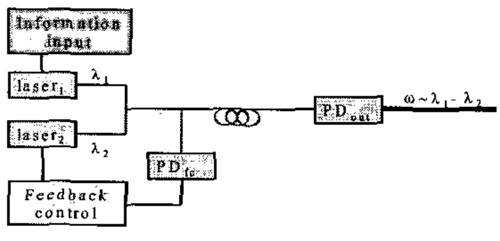


Fig.1. Simplified diagram of the DTMOT. Communication or coding signals can directly modulate the lasers.

Suitable control of pump power and/or temperature of either one of the lasers provides for an independent, course adjustment of its wavelength, and hence the beat frequency of the heterodyned millimeter wave signal. Rapid, dynamic frequency tuning is accomplished by applying an external voltage to the electrodes of the $LiNbO_3$ tuning section. The measured tuning rate is at least 88 GHz/microsecond (limited by the driving circuit) and the sensitivity is over 22 MHz/V. The next generation of lasers, using a thinner (.1mm) $LiNbO_3$ tuning slab, are expected to have a tuning sensitivity of 100 MHz/V or higher. Although the experiments reported in this paper are at or below 40 GHz due to the unavailability of very high speed photodetectors in our laboratory, the laser system itself can generate millimeter wave signals up to approximately 200 GHz (limited by the gain profile of the $Nd:YVO_4$). For example, the optical spectra of a pair of lasers depicted in Fig. 3 reveals a wavelength separation of 0.46nm and 0.68nm, which correspond to frequency separations of 80GHz and 120GHz respectively.

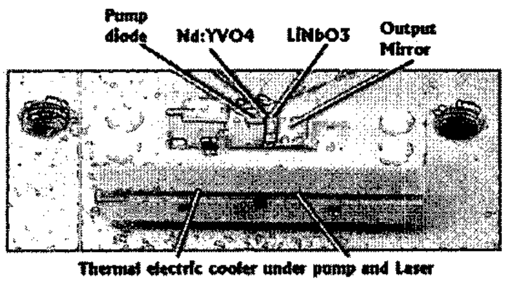
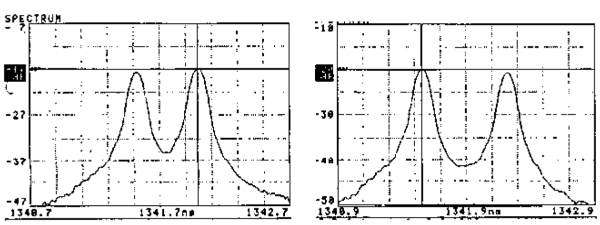


Fig. 2. Tunable microchip laser module.



a.) b.)

Fig.3. The optical spectra of a pair of lasers. The separation of the lasing wavelengths, ~80 GHz for a.) and ~ 120 GHz for b.), were achieved by adjusting the temperature and/or the pump power biasing to the lasers.

III. Frequency Stabilization And Phase Noise Measurements

In the configuration described above, the laser transmitter-photodetector combination acts as a voltage controlled oscillator (VCO). Accurate frequency tuning and stabilization requires the introduction of a control mechanism. There are many methods available, but conventional synthesizers often employ a phase-locked loop (PLL) comprised of a set of digital counters and a reference oscillator [3]. Extensive research on the optical generation of millimeter waves has been carried out by Seeds and his coworkers [4-7]. They employed semiconductor lasers and an optical phased locked loop (OPLL), sometimes in combination with injection locking. At 35 GHz they achieved a phase noise of -94 dBc/Hz at a 10kHz offset.

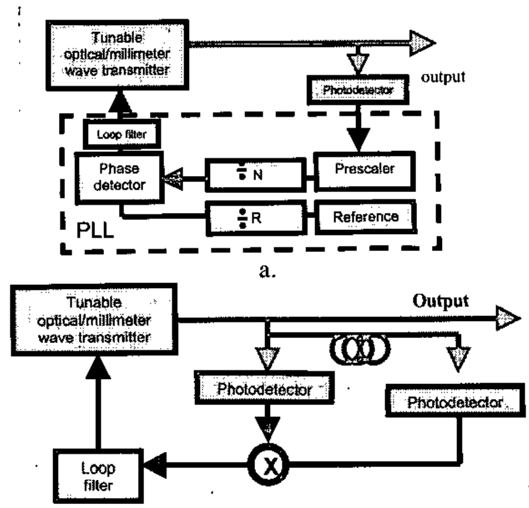
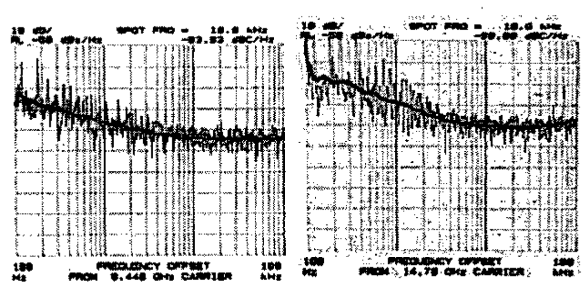


Fig. 4. Frequency stabilization: a. PLL, and b. OFLL.

In previous work [1,2], we have implemented the VCO-PLL combination with the simplified diagram shown in Fig. 4a. Using the digital synthesizer approach, the DTMOT is locked to a 133 MHz crystal reference. The measured phase noise for 8.44 GHz and 40 GHz carrier signals is shown in Fig. 5.



a). b).

Fig. 5. Phase noise spectrum of PLL output signal. a). Phase noise of 8.44GHz signal, and b). Phase noise of 40GHz signal mixed down to 14.78 GHz

At 8.44GHz, the measured phase noise is –93.8dBc/Hz at 10kHz offset, which is 14 dB higher than the theoretical reference floor. Jitter in the PLL counters and loop filter noise account for the difference between the theoretical and measured results.

To lock and characterize the 40GHz carrier signal, a secondary reference is employed to mix down the 40GHz signal to approximately 14.78 GHz. This is required due to the frequency limitation of the prescaler used in the PLL. The phase noise measurement was made at the lower frequency to eliminate the noise contribution from the secondary reference source. The measured phase noise at a 10kHz offset is −90dBc/Hz. Our theoretical analysis indicates that better performance would depend primarily on an improved synthesizer and is not fundamentally limited by the lasers.

The advantages of the synthesizer approach include: simple low cost circuitry, direct control of output frequency, relatively fast frequency selection (channel tuning), automatic recovery from loss of lock, and excellent frequency accuracy (determined by the reference oscillator). However, the lack of availability and cost of high frequency (millimeter wave) digital electronics, the jitter and noise of the digital dividers, and the unavoidable 20dB/decade escalation of phase noise with increasing frequency restrict the ultimate performance of synthesizers. These considerations prompted a search for an alternate solution. The inspiration came from the work of Yao et. al.[8-9], namely the use of fiberoptic delay line for signal processing. A novel approach, coined the Optical Frequency Locked Loop (OFLL), depicted in Fig. 4b, was developed for our experiments.

The OFLL fiberoptic feedback loop has two arms. One arm is very short (a few cm), while the other arm is a .1 to 0.5 km long fiberoptic spool. The output from the two photodiodes (one for each arm) is mixed and fed back into the laser assembly though a suitable loop filter. Unlike the PLL, the OFLL does not require a low phase noise reference. The fiberoptic delay loop produces a sequence of equally spaced nodes in the frequency domain, which can be tuned in several ways (e.g. by a fiber stretcher or by temperature). The OFLL functions by locking the heterodyned laser signal to one of these nodes.

The principal advantages of the OFLL are that there is no need for a low phase noise reference source and that the phase noise is nearly independent of operating frequency, which can be continuously tuned. Among the disadvantages of the OFLL are the need for two high-speed photodetectors and temperature and mechanical stability of the fiber spool. A reference is still needed to maintain long-term frequency accuracy, but it doesn't need to have low phase noise. Therefore the OFLL may have significant advantages, particularly at higher millimeter wave frequencies.

The simple OFLL depicted in Fig. 4b, sustains significant phase noise degradation due to the laser AM noise to sub carrier phase noise conversion, which occurs if the mixer used for the phase detector is not perfectly balanced. Therefore, an improved version of the OFLL, illustrated in fig.6, was investigated.

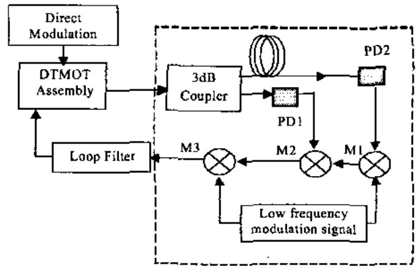
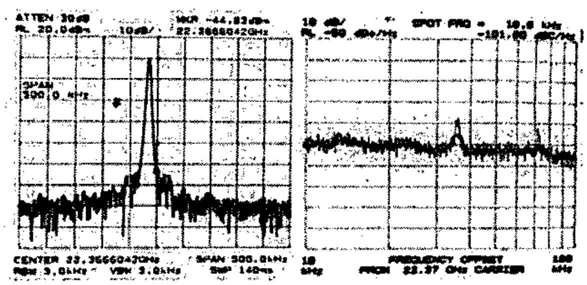


Fig. 6 Optical frequency locked loop (OFLL) implementation.

For this version of OFLL, the sub carrier phase error is transferred to the phase noise of a fixed, low frequency signal, which is set at 7 GHz in our experiments. This is accomplished by first down converting the delayed millimeter wave signal at the output of photodetector 2 (PD2) at mixer 1 (M1) and then again mixing this signal with the output of photodetector 1 at M2. The phase error is later recovered by demodulation at mixer 3 (M3). Mathematical model predicts that the suppression of the AM noise to phase noise conversion depends on the modulation index of the down converted signal and the power ratio of the sub carrier signals in the delayed and non-delayed paths. If the signal amplitudes in the two paths are equal, the AM to phase noise conversion is suppressed by 20 dB with 20 dB AM modulation index. In addition, the phase noise of the improved OFLL is a function of the AM noise, but is independent of the phase noise of the low frequency modulation signal Next, we present our first results with this DTMOT- OFLL arrangement.

The specific system used for our experiments consists of a pair of microchip lasers with their beams combined with free-space optics and a delay line length of .150 km. The optical power coupled into a single mode fiber was −2dBm, which generated −32 dBm of microwave power at the two photodiodes. The spectrum and phase noise of the heterodyned signal at 22GHz is shown in Fig. 6. The phase noise is independent of frequency over the range the two photodetector-amplifier subsystems have matched, flat frequency responses.

Our theoretical study indicates that the phase noise of the OFLL is an intense function of the effective signal-to-noise ratio at the photodiode output. In the presently assembled OFLL system, the mm-wave power out of the photodetector is −32dBm, and the amplifier following the photodetector has a gain of 40dB and a noise figure of 6dB. The predicted system noise floor, including the .15 km delay line is −110dBc/Hz at a 10kHz offset, while the actual measured phase noise at 10kHz is −101dBc/Hz, or 9dB higher. The fact that the phase noise floor is very flat from 10 to 100 kHz seems to imply that the measurement has hit the AM noise floor of the system. Thus, the actual phase noise may be lower. Since the balanced mixer is not ideal, the conversion of the laser RIN noise to phase noise may also contribute to the measurements. Finally, the two spurs appear in the measured phase noise spectrum at 37 kHz and 70 kHz offset were traced to the commercial laser diode driver and the microwave spectrum analyzer, respectively.



a). b).

Fig. 6 The signal spectrum and phase noise of 22GHz optical delay line frequency locked loop. a). Signal spectrum, and b). Phase noise spectrum.

IV. Discussion.

Heterodyned lasers can produce extremely high frequencies and the practical limit is defined by the photodetector-amplifier sub-system, which is 40 GHz in our laboratory and about 75 GHz for commercially available units. Continued improvements in photodetector performances are expected too extend this limit to 100 GHz or higher. Employing propagation delay time as a reference in place of an electronic reference appears to have significant advantages. The phase noise is low and independent of frequency.

Our theoretical model predicts that the noise performance of the improved OFLL is ultimately limited by the system thermal noise and photo detector shot noise, not by the laser RIN noise. By increasing the optical power output, most notably the coupling efficiency from the microchip laser to single mode fiber, we expect to generate a 10dB increase in optical power, which should result in a 20dB decrease in the phase noise floor. In addition, any increase in the optical power also leads reduce amplifier gain, which implies a lower OFLL AM noise floor.

In our theoretical analysis, the phase noise performance of the delay line synthesizer also depends on the fiber delay line length. A longer delay line would further reduce the close-in phase noise. However, it will also reduce the system stability. Optimization of the fiber delay line would further improve the system performance.

In conclusion, by increasing optical coupling and proper fiber length selection, -120dBc/Hz at 10kHz noise performance should be expected.

The DTMOT has application in lidar-radar systems for surveillance and medical imaging systems where low noise and very rapid chirping is required [1]. As previous reported, these microchip lasers can be effectively modulated with communication signals [2]. Employing a number of laser modules in parallel, we can generate several millimeter wave channels separated by a few GHz, and impose an MSK communications signal on each channel. This leads to an orthogonal frequency multiplexed wireless transmitter, a variation on the fiber-radio concept. The rapid tunability combined with the low noise carrier generation is also exploited in a frequency agile communication system.

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