Optoelectronic Phase Locking of Microwave Signals Up to 4 GHz Using a Laser-Diode-Based Electrooptic Harmonic Mixer

Ci-Ling Pan, Kai-Yuan Tang, and Hsiao-Hua Wu

Abstract—**A reflection-mode GaAs electrooptical sampler has been used for constructing a harmonic mixer to optoelectronically phase-lock microwave signals up to 4 GHz in a laser-diode-based system. The conversion loss of the harmonic mixer is 81 dB. The phase noise degradation of the phase-locked 4-GHz signal at 5-kHz offset measured with respect to the 500 MHz synthesizer signal driving the laser diode is 38 dB.**

I. Introduction

For measurement of cw microwave signals in discrete devices or MMIC's by either photoconductive [1]–[3] or electrooptic [4]–[6] sampling techniques, it is important to maintain phase coherence or time synchronization between the microwave signal and optical pulse train. To accomplish this, we have recently demonstrated a laser-diode-based optoelectronic phase lock loop (OEPLL) [7]. The key element of this OEPLL is a laser-diode-activated GaAs–Cr photoconductive switch that functions as an optoelectronic harmonic mixer (OEHM) for intermixing microwave and optical signals. The electrooptic effect in GaAs microstrip circuits can also be used in the OEHM. The electrooptic harmonic mixer (EOHM) is attractive because the laser pulse train can be used to phase-lock the microwave signal at any arbitrary point in the MMIC. This approach was first demonstrated by the Maryland group using a main frame mode-locked laser [8]. It is desirable to use a diode laser, which is compact, has high repetition rate and exhibits minimum timing jitter, in such a system. In this letter, we present for the first time to our knowledge, optoelectronic phase-locking of microwave signals up to 4 GHz by a laser-diode-based GaAs electrooptic harmonic mixer.

II. Experimental Methods

Our experimental apparatus is shown in Fig. 1. The EOHM is an electrooptic sampler consisting of a 50-Ω microstrip line fabricated on undoped semi-insulating (SI) LEC-grown GaAs substrate. The standard reflection-mode probing geometry is used. A train of 30-ps optical pulses at 500 MHz from the gain-switched laser diode (Toshiba, model TOLD-300, $\lambda = 1.3\mu$m) with an average power of 0.4 mW is sent through a polarizing beam splitter (PBS), a quarterwave plate (QWP), a half-wave plate (HWP) and focused on the ground plane of the microstrip line. In the phase-locking experiment, free-running microwave signal from a sweep oscillator (HP8620C) at a power level of −8.4 dBm is fed to the microstrip line via a power amplifier with 30-dB gain. The microwave signal changes the polarization of the reflected optical pulses which passes back through the lens and the wave plates, then directed by the PBS to an InGaAs photodiode (PD). The buffered output of the PD is further amplified by two stages of low-noise amplifiers with a combined gain of 52 dB and mixed with a reference signal at the desired intermediate frequency, $f_{\rm IF}$. The resultant error signal is used to phase-lock the sweep oscillator which operates as a voltage-controlled oscillator (VCO) via a loop filter. The expected phase-locked frequency of the VCO is $F = (Nf_o \pm f_{\rm IF})$, where N is an integer.

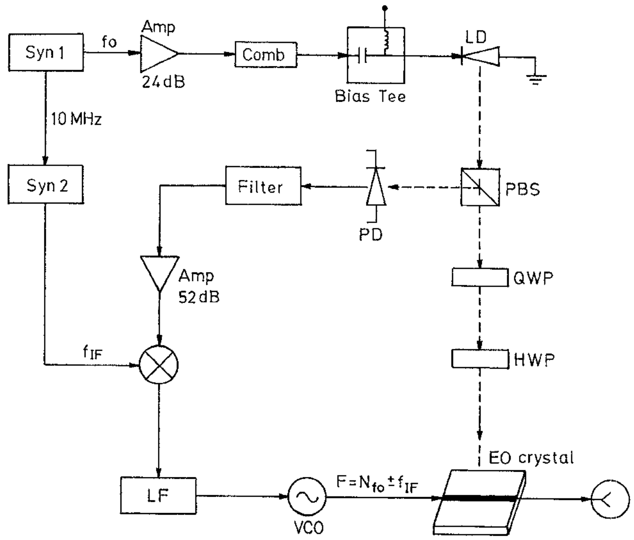

Fig. 1. Schematics of the experimental set up. Syn1 and Syn2 are frequency synthesizers; Comb: comb generator, LD: laser diode, LF: loop filter.

III. Results and Discussions

For an average photocurrent, $I_{\rm avg} = 30\mu A$, the conversion loss of the EOHM from the microwave signal (at 500 MHz and 21.6 dBm) to the IF is measured to be 81 dB. In comparison, phase locking using a laser-diode-based GaAs–Cr photoconductive harmonic mixer (PCHM) [7] under the same

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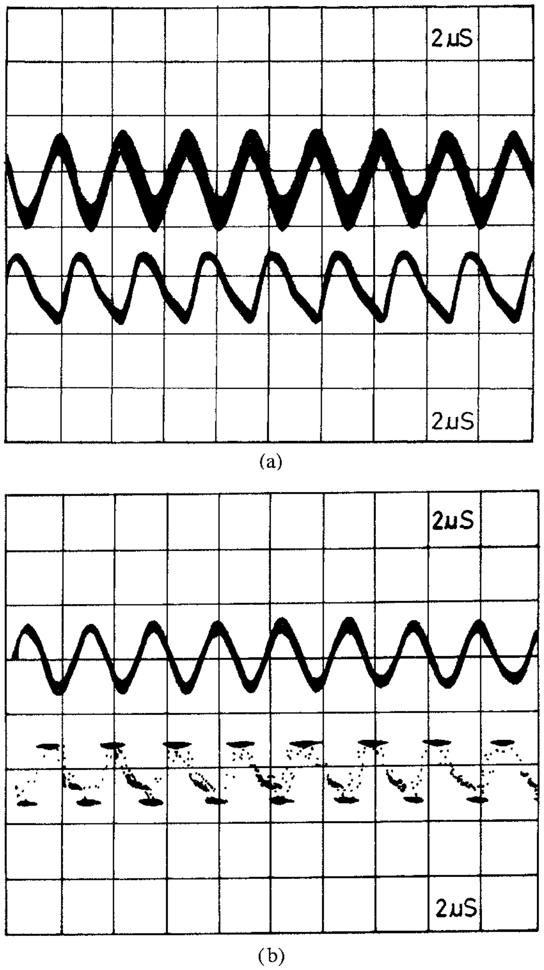

Fig. 2. (a) Upper trace: 400 kHz reference signal; lower trace: electrooptic sampled replica of the photoconductively phase-locked 500 MHz signal at the intermediate frequency, $f_{\rm IF} = 400$ kHz.(b) Upper trace: 400 kHz reference signal; lower trace: photoconductively sampled replica of the electrooptic phase-locked 500 MHz signal at the intermediate frequency, $f_{\rm IF} = 400$ kHz.

condition (same microwave power, loop filter, and IF) yields conversion loss of 42.8 dB. The waveform of the photoconductively phase-locked 500 MHz signal has been sampled and displayed via a low-frequency replica at 400 kHz by an electrooptic harmonic mixer (EOHM) and shown in Fig. 2(a) [9], [10]. Similarly, the waveform of an electrooptically phase-locked 500 MHz signal as displayed via a replica at 400 kHz by a photoconductive harmonic mixer is shown in Fig. 2(b). These results clearly show that the performance of the OEPLL employing the EOHM is inferior to that with a PCHM both in terms of the conversion loss, under our experimental conditions. On the other hand, the EOHM is more versatile than the PCHM as the latter requires incorporation of a photoconductive switch on the MMIC. We are able to electrooptically phase-lock the VCO up to 4 GHz. The spectrum of the 4-GHz optoelectronically phase-locked spectrum is shown in Fig. 3. The phase noise degradation of the electrooptically phase-locked 4–GHz signal at 5-kHz offset measured with respect to the 500-MHz signal driving the laser diode is 38 dB. Phase locking at higher frequencies would be possible if broadband power amplifiers are available. It is also interesting to compare the laser-diode-based EOHM

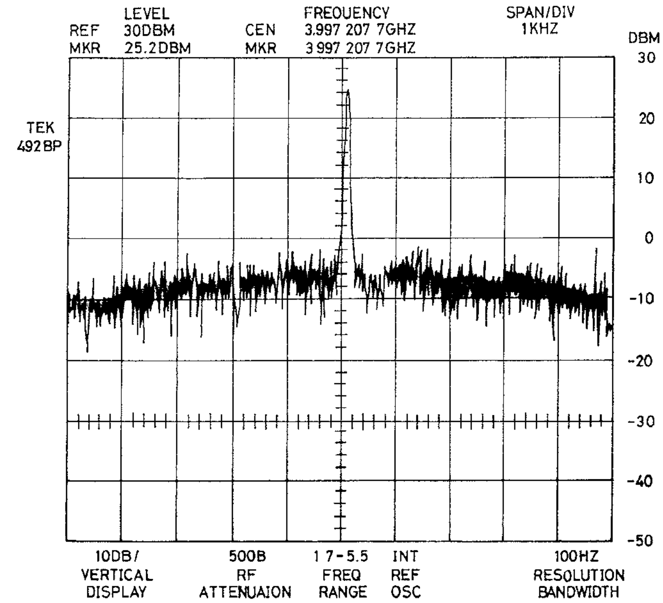

Fig. 3. Spectrum of the 4GHz electrooptically phase-locked signal (resolution BW=100 Hz, frequency span = 1 kHz/div., vertical scale = 10 dB/div).

with a system using a main-frame laser. For the latter case, $I_{\rm avg} \approx 1mA$, a reasonable estimate for the conversion loss would be 61 dB. Obviously, high-power laser diode will drastically improve the performance of the laser-diode-based EOHM. Increasing the load resistance, R_L, and narrowing the IF bandwidth are also expected to be helpful. Improvement of the OEPLL by optimizing these parameters is limited and may degrade the tracking performance of the PLL. The optimum value of $f_{\rm IF}$ for the present OEPLL is 400 kHz with the load resistance for the PD, $R_L = 50$ kΩ. This is in contrast to typical electrooptic sampling experiments which operate at several MHz due to the noisier main-frame laser. We note that other types of electrooptic modulators with lower half-wave voltage, V_π, such as an integrated-optic Mach–Zehnder type electrooptic modulator, can be used as the EOHM. The sensitivity of the electrooptic sampler can also be increased by using an organic patch sensor. [11]

IV. Conclusion

In summary, we have demonstrated phase-locking of optical and microwave signals up to 4 GHz using a compact laser-diode-based GaAs electrooptic sampler as an optoelectronic harmonic mixer in the PLL. Comparisons of the present approach with systems employing main-frame lasers or a photoconductive switch as the harmonic mixer are also presented. The upper bound for the frequency of the phase-locked signal in the present work is limited by the available average power and pulse width of the laser diode, as well as V_π of the GaAs material. We have also suggested methods for alleviating these problems such that our scheme can be used for phase locking of optical and millimeter-wave signals at the wafer level.

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REFERENCES

[1] H.-L. A. Hung, P. Polak-Dingels, K. J. Webb, T. Smith, H. C. Hunag, and C. H. Lee, "Millimeter-wave monolithic integrated circuit characterization by a picosecond optoelectronic technique," *IEEE Trans. Microwave Theory Tech.* vol. 37, pp. 1223–1230, Aug. 1989.

[2] M. Matloubian, S. E. Rosenbaum, H. R. Fetterman, and P. T. Greiling, "Wide-band millimeter wave characterization of sub-0.2 micrometer gate-length AlInAs/GaInAs HEMT's," *IEEE Microwave Guided Wave Lett.*, vol. 1, pp. 32–34, Feb. 1991.

[3] D. H. Auston, "Picosecond photoconductivity: High-speed measurements of devices and materials," in *Measurement of High Speed Signals in Solid State Devices, Semiconductors and Semimetals*, vol. 28, R. B. Marcus, Ed. New York: Academic Press, 1990, pp. 85–134.

[4] M. J. W. Rodwell, M. Riaziat, K. J. Weingarten, B. A. Auld, and D. M. Bloom, "Internal microwave propagation and distortion characteristics of traveling-wave amplifiers studied by electrooptic sampling," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1356–1362, Dec. 1986.

[5] K. J. Weingarten, M. J. W. Rodwell, and D. M. Bloom, "Picosecond optical sampling of GaAs integrated circuits," *IEEE J. Quantum Electron.*, vol. 24, pp. 198–220, Feb. 1988.

[6] J. M. Weingarten and M. S. Heutmaker, "Frequency response of an internal amplifier in a high-speed integrated circuit measured by electrooptic sampling," *Electron. Lett.*, vol. 24, pp. 106–107, Jan. 1988.

[7] H.-H. Wu, C.-S. Chang, and C.-L. Pan, "Optoelectronic phase-locking of microwave signals up to 18GHz by a laser-diode-based GaAs:Cr photoconductive harmonic mixer," *IEEE Microwave Guided Wave Lett.*, vol. 2, pp. 11–13, Jan. 1992.

[8] M. G. Li, E. A. Chauchard, C. H. Lee, and H.-L. Hung, "Intermixing optical and microwave signals in GaAs microstrip circuit for phase-locking applications," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1924–1931, Dec. 1990.

[9] M. G. Li, S.-L. L. Hung, C. H. Lee, and H.-L. A. Hung, "Display of microwave waveform via a low frequency replica using an optical phase-locking and sampling technique," in *Picosecond Electronics and Optoelectronics* (Technical Digest Series), Optical Society of America, Washington, DC, 1988, pp. 24–27.

[10] H.-H. Wu, C.-S. Chang, and C.-L. Pan, "A laser-diode-based photoconductive harmonic mixer for microwave waveform and spectrum measurements," *IEEE Microwave Guided Wave Lett.*, vol. 2, pp. 273–275, July 1992.

[11] T. Nagatsuma, M. Yaita, M. Shinagawa, M. Amano, and Y. Shuto, "Organic patch sensor for electrooptic measurement of electrical signals in integrated circuits," *Electron. Lett.*, vol. 27, pp. 932–934, May 23, 1991.