Electrooptic Phase Tracking of Microwave Signals Beyond 18.5 GHz Using an Integrated Electrooptic Modulator as an Optoelectronic Harmonic Mixer in a Phase Lock Loop

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***Abstract*— We demonstrate electrooptic phase tracking of microwave signals beyond 18.5 GHz using a gain-switched laser diode as the optical clock. The key element of this system is a fiber-pigtailed integrated-optic Mach–Zehnder Modulator (IOM). The IOM functions as an optoelectronic harmonic mixer in a phase lock loop. The conversion loss of the OEHM is 66dB. The phase error and the single sideband phase noise density of the phase- locked 18.5 GHz signal is 5.6×10^{-5} rad/$\sqrt{\text{Hz}}$and -54 dBc/Hz, respectively.**

I. Introduction

RECENTLY, the application of lightwave technology to microwave and high-data-rate communication systems has attracted much attention [1]–[3]. For many of these applications, phase coherence or time synchronization between the master clock and network of distributed oscillators is mandatory [4]. Precision phase referencing is also important in electrooptic or photoconductive sampling of high-speed devices and circuits [5]–[7]. We have previously demonstrated compact laser-diode-based optoelectronic phase lock loops (OEPLL's) that allow phase locking of microwave oscillators with an optical clock [8], [9]. The key element of our OEPLL can be either a photoconductive switch or a bulk electrooptical sampler that functions as an optoelectronic harmonic mixer (OEHM). The microwave signal of interests is intermixed with the desired higher spectral harmonics of the laser pulse train in the OEHM. The phase of the down converted baseband signal at the offset or intermediate frequency (IF), f_{IF}, is compared with that of a reference signal and generates the error signal for the OEPLL. Non-offset type OEPLL with $f_{\text{IF}} = 0$ has also been reported [10]. In this letter, we demonstrate phase tracking of microwave signals to an optical clock using an integrated-optic electrooptic modulator (IOM) as the OEHM. The IOM is shown to exhibit a significantly lower conversion loss from microwave to the IF than the bulk electrooptic sampler. Furthermore, the fiber-pigtailed IOM is intrinsically compatible to the fiber-optic link. This technique is thus ideal for applications such as synchronization in fiber-optic microwave distributed networks and signal recovery in fiber-optic communication systems.

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II. Experimental

The experimental arrangement is illustrated in Fig. 1. The optical clock is provided by a fiber-pigtailed DFB laser diode (Toshiba TOLD312$S, \lambda = 1.3\mu m$), which is gain-switched to generate a train of $\simeq 40ps$ optical pulses at 500 MHz. The fiber-output of the laser is fusion-spliced with an integrated-optic Mach–Zehnder-type, electrooptic modulator (IOM). Two commercial IOM's have been tested: a Crystal Technology model $MZ313P$(with an experimentally determined 3-dB bandwidth, $BW \simeq 3$ GHz, and $V_\pi \simeq 10V$) and a New Focus model 4503 (with $BW \simeq 5$ GHz and $V_\pi \simeq 22V$). The insertion loss of the IOM is $\approx 6dB$. In the phase-locking experiment, the IOM is amplitude-modulated by microwave signals from a free-running sweep oscillator ($HP8620C$), working in the cw mode. The IOM-photodetector combination functions as the OEHM. Therefore, the microwave signal is intermixed with various harmonics of the laser pulses to generate the desired signal at an offset or intermediate frequency at the output of the photodetector (IF), f_{IF}. After phase comparison of the IF with a reference signal, the resultant error signal is used to allow phase-tracking by the sweep oscillator, which operates as a voltage-controlled oscillator (VCO) via an active loop filter. The expected phase-locked frequency of the VCO is thus $f_m = Nf_o \pm f_{\text{IF}}$.

III. Results and Discussions

Using the $MZ313P$ or the NewFocus 4503 as the IOM, we are able to achieve phase tracking of microwave signals up to 12 GHz and beyond 18.5 GHz, respectively. With the 4503, the upper boundary for the phase-locked frequency is limited by the available VCO in this experiment. Higher frequency could be locked with the present system. In the following, we limit our discussion to data for the 4503.

With an average photocurrent, $I_{\text{avg}} = 13\mu A$, the IF signal asmeasured at the output of the photodetector is -48 dBm, in response to a microwave signal ($f_m = 500$ MHz) at the

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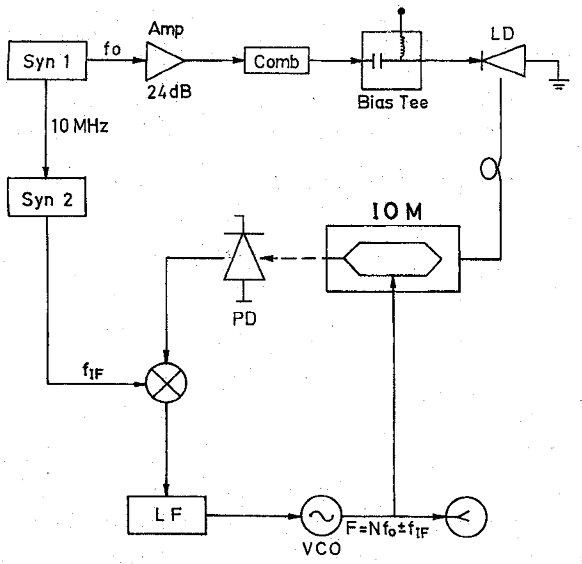

Fig. 1. Schematics of the experimental setup. Syn 1 and Syn 2 are frequency synthesizers; comb: comb generator, LD: laser diode, LF: loop filter.

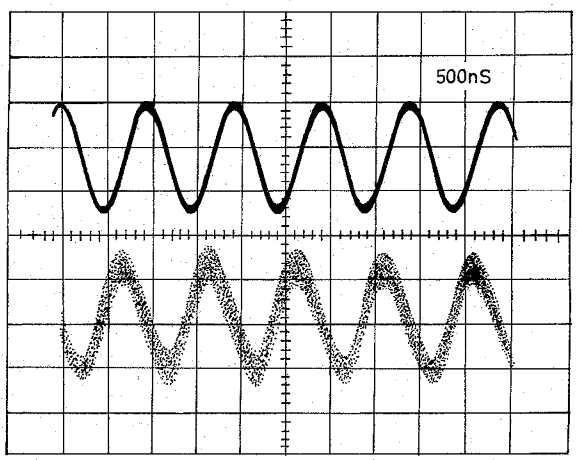

Fig. 2. 18.5-GHz electrooptically phase-locked signal as monitored on an oscilloscope (upper trace: 1-MHz intermixed signal; lower trace:1-MHz reference signal from syn 2).

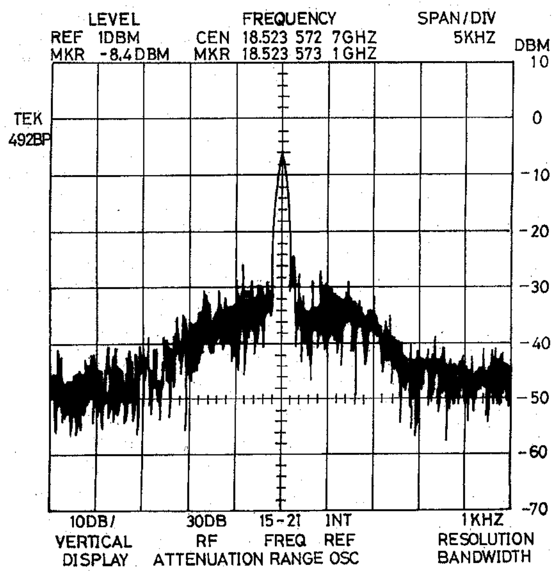

Fig. 3. Spectrum of the electrooptically phase-locked VCO at 18.5 GHz. (resolution BW = 1kHz, frequency span = 5kHz/div., vertical scale= $10dB/$div.)

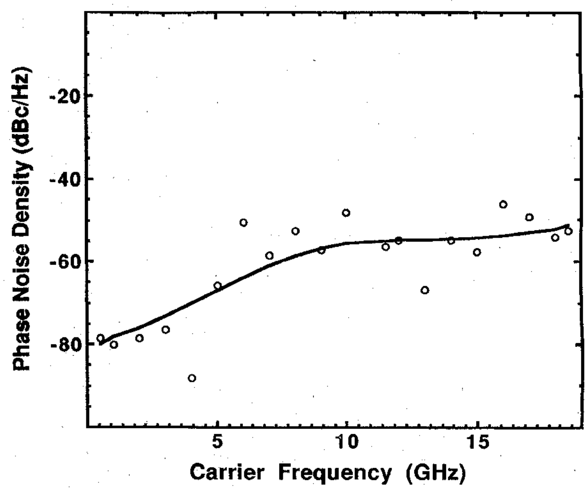

Fig. 4. Single sideband phase noise density for frequency offset within 5 kHz of the carrier measured at different carrier frequencies.

power level of -9.2 dBm. This corresponds to a conversion loss of $39dB$. In comparison, the conversion loss of the bulk GaAs electrooptic sampler as the OEHM ($I_{\text{avg}} = 30\mu A$) is $81dB$[9]. Furthermore, the microwave power used is about $30dB$ higher and the photodetector output is amplified by $52dB$(as opposed to $26dB$) in the previous experiment. The significant improvement in conversion loss can be attributed to the $10^4 - 10^5$ difference in $V_\pi(22V$ for the IOM versus $5.4kV$ for bulk GaAs). The conversion loss increases to $66dB$ as the frequency of the microwave signal increases to 18.5 GHz. If phase tracking is achieved, clean waveform of the phase-locked IF signal (Fig. 2, lower trace) mixed down from the microwave signal at 18.5 GHz can be observed on the oscilloscope triggered by the reference signal at 1 MHz (upper trace, Fig. 2). With a measurement bandwidth of $20Hz$, the error voltage measured at the output of the phase detector in the loop is less than $0.5mV$. This corresponds to phase tracking with a residue phase error of $2.5x10^{-4}$ rad, calculated using the gain factor of the phase detector, $2v/$rad.

Fig. 3 displays the sideband spectrum of the phase-locked VCO at 18.5 GHz, from which we estimated that the single sideband phase noise density is below -54 dBc$/Hz$ for frequency offsets within 10 kHz of the carrier. The same type of measurement was also performed at different carrier frequencies and results are presented in Fig. 4. An increase in noise density of about $20dB$ can be observed for carrier frequencies above 5 GHz. Nevertheless, it is worth nothing that phase tracking is possible at frequencies much higher than $3dB$ bandwidth of the IOM ($BW \simeq 5$ GHz for the 4503) and laser pulse width ($\tau \simeq 40ps$ or $BW \simeq 10$ GHz) used.

The use of laser diodes with higher average power will improve the performance of the present OEHM, as the conversion loss is inversely proportional to $(I_{\text{avg}})^2$ and the signal-to-noise ratio is proportional to I_{avg}. Increasing the load resistance, R_L, and narrowing the IF bandwidth are also expected to be helpful. For the present system, $R_L = 100k\Omega$ and the IF bandwidth is in excess of 600 kHz. Phase tracking of millimeter wave oscillators using the IOM as the OEHM in the PLL is feasible as IOM with bandwidth up to 94 GHz [11] and laser diodes generating subpicosecond pulses [12] have been reported in the literature.

IV. Summary

In this letter, we report phase tracking of microwave signals beyond 18.5 GHz using an IOM with 3-dB bandwidth of 5 GHz and $V_\pi = 22V$ as the OEHM in the PLL. The optical clock is provided by $40ps$ pulse train from a gain-switched laser diode operating at 500 MHz. The conversion loss of the OEHM, noise characteristics of the phase-locked signal, as well as comparison with previous approaches are also presented. The upper bound for the frequency of the phase-locked signal is primarily determined by the average power and pulse width of the gain-switched laser diode, as well as V_π and $3dBBW$ of the IOM. With state-of-the-art devices, optoelectronic synchronization of MMIC oscillators for various applications using the present approach can be easily realized.

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