Laser-Diode-Based Optoelectronic Subharmonic Phase-Locked Loop

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***Abstract*—An optoelectronic technique for synthesis of frequency-versatile electrical signals phase-locked to the optical clock is proposed. The key component is an integrated-optic modulator (IOM) operated in the nonlinear regime. With a photodetctor, the IOM functions as an optoelectronic subharmonic mixer for intermixing microwave signals that are subharmonics of the optical clock. As a first demonstration, phase-locked subharmonics and fractional harmonics of the optical clock at $f_o = 500$ MHz, with frequency equal to f_o/n or $(m/n)f_o$, where $n = 2,3,4\ldots$ and $m/n = 2/5, 2/3, 4/3, 3/2$ and $5/3$ etc., are generated and characterized.**

I. Introduction

THE phase lock loop (PLL) is a well-established technique for the synchronization, i.e., maintaining phase coherence, of electrical signals. One of the most important applications of the PLL in electronic systems is the phase-locked synthesizer. In its simplest configuration the harmonic PLL, a frequency multiplier, is incorporated to generate the desired harmonics of a stable frequency reference at frequency f_o for phase locking of the voltage-controlled oscillator (VCO) operating at $f_v = mf_o$. Conversely, the phase-locking condition is described by $nf_v = f_o$ in the fractional harmonic (or subharmonic) PLL [1]. In the above, m, n are integers. A harmonic mixer that functions both as a harmonics generator and a frequency down-converter is a key element in harmonic phase-locking systems for frequency synthesis.

Techniques for the generation and control of electrical signals, such as the PLL, can benefit from recent advances in optical technology. In particular, optoelectronically phase-locked synthesizers are potentially useful devices for antenna remoting and other applications involving optical-microwave interactions. They are also intrinsically compatible with fiber-optic distributed networks. Recently, several laser-diode-based optoelectronic phase locking systems that utilize optoelectronic components in the PLL circuit have been demonstrated. In these optoelectronic phase-locked loops (OEPLL's), the key element is an optoelectronic transferring device or optoelectronic harmonic mixer (OEHM). Electrical signals are intermixed with the higher harmonics of the optical clock pulses (the local oscillator signal) in the OEHM to generate the down-converted intermediate frequency signal. Bulk electrooptic samplers [2]–[4], photoconductive switches [5], and integrated-optic modulators (IOM) [6], [7] have been successfully employed as OEHM's. For example, phase locking beyond 18.5 GHz or the 37th harmonic of the optical clock pulses at $f_o = 500$ MHz has been demonstrated with an IOM in the OEPLL. In this work, we demonstrate for the first time optoelectronic subharmonic phase locking for the remote generation of stable, frequency-versatile electrical signals at f_o/n or $(m/n)f_o$, where n, m are integers.

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II. Operation Principles

In our previous work for optoelectronic harmonic phase locking [7], a gain-switched laser diode provided optical clock pulses. The IOM was small-signal-modulated, i.e., operating in the linear regime. For subharmonic phase locking, the laser diode is small-signal-modulated while the IOM is operated in the nonlinear regime and modulated by the VCO oscillating at the desired subharmonics. It is well-known that an IOM biased at the maximum (or minimum) output and linear output points (i.e. $V_{\mathrm{DC}} = 0$ or V_π, and $V_\pi/2$) would generate sidebands of the optical carrier, which are even and odd harmonics of the modulation frequency, respectively. On the other hand, at $V_{\mathrm{DC}} = V_\pi/4$ and $3V_\pi/4$ all the harmonics are generated and the transfer functions of the IOM can be written as

$$I = (I_0 + I_1 \cos\omega_0 t)\left\{1 \pm \frac{\sqrt{2}}{2} J_0\left(\frac{\pi V_{\mathrm{RF}}}{V_\pi}\right) \pm \sqrt{2}\sum_{n=1}^{\infty}\left[J_{2n}\left(\frac{\pi V_{\mathrm{RF}}}{V_\pi}\right)\cos 2n\omega_v t + J_{2n-1}\left(\frac{\pi V_{\mathrm{RF}}}{V_\pi}\right)\sin(2n-1)\omega_v t\right]\right\} \quad (1)$$

where $\omega_0 = 2\pi f_o$ and $\omega_v = 2\pi f_v$. The plus and minus signs in (1) correspond to the IOM biased at $V_{\mathrm{DC}} = V\pi/4$ and $3V\pi/4$, respectively. Clearly, a set of subharmonics that satisfy the condition $f_v = f_o/n$ (n is an integer), is available for intermixing with the modulated optical wave at the photodetector. In order to obtain the fractional harmonics, one can increase the RF modulation depth for the laser diode so that several harmonics of f_o are present. In (1), the term $\cos\omega_0 t$ would be replaced by a sum of harmonic terms, $\cos m\omega t$, each multiplied by appropriate amplitude factors. The condition for fractional harmonic phase locking is then $nf_v = mf_o$, where m, n are integers.

III. Experimental

A schematic of the experimental setup is shown in Fig. 1. A fiber-pigtailed distributed feedback (DFB) laser diode (Toshiba

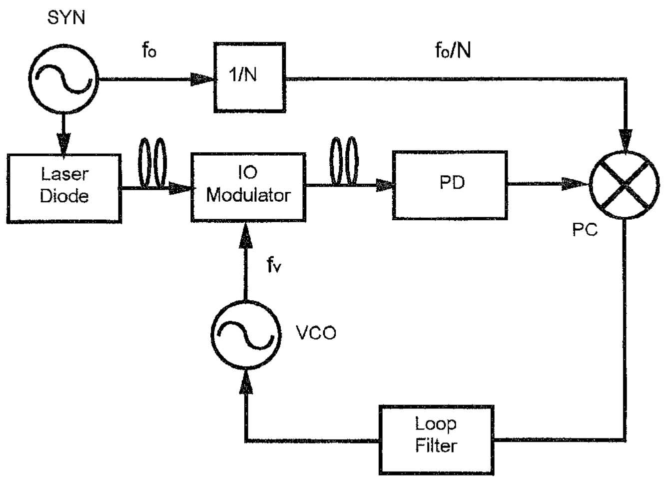


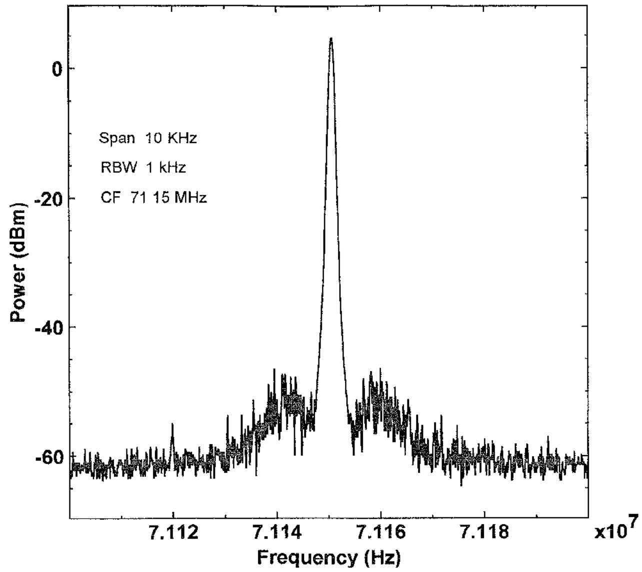
Fig 1 Block diagram of the optoelectronic subharmonic phase-locking system. PC: phase comparator, PD: photodetector, Syn: synthesizer.

TOLD312S, $\lambda = 1.3$ μm) is directly modulated by a microwave synthesizer (Anritsu MG3601A) operating at $f_o =$ 500 MHz and 12 dBm. The output of the laser is fusion-spliced with a Mach-Zehnder-type IOM (New Focus model 4503). The 3-dB bandwidth and halfwave voltage (V_π) of the IOM are approximately 5 GHz and 22 V, respectively. The intrinsic offset bias of the IOM is about 2 V. The insertion loss of the IOM is rated at $\approx$6 dB by the manufacturer. In our experiment, the amplified output (30 dBm) of a sweep oscillator (HP8620C) working in the cw mode is employed for amplitude modulation of the IOM. The down-converted optoelectronic signal at an offset or intermediate frequency (IF) $f_{\mathrm{IF}} = 1.95$ MHz, is fed to an analog phase comparator (EXAR X2208). After phase comparison of the IF signal with a reference signal obtained from a direct division of the optical clock frequency (the dividing number is 256), the resultant error signal is used to allow phase-tracking of the optical clock by the sweep oscillator via an active loop filter. The expected phase-locked subharmonic or fractional harmonic frequency of the V_{CO} is $f_v = (f_o \pm f_{\mathrm{IF}})/n$ or $(f_o \pm f_{\mathrm{IF}})m/n$, where m, n are integers.

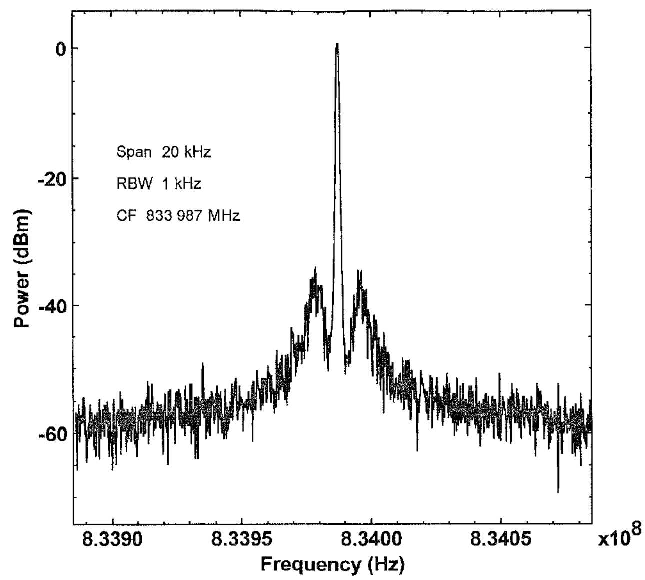
IV. Results and Discussions

Through fine adjustments of the parameters of the loop filter (usually the variable resistors inside the active loop filter), we are able to generate a number of subharmonics at $f_v \approx f_o/n$, with $n = 2, 3, 4, \ldots$ and fractional harmonics at $(m/n)f_o$, with $m/n = 2/5, 2/3, 4/3, 3/2$, and $5/3$ etc.. As an example, the power spectrum of the 7th subharmonic and the 5/3 fractional harmonic phase locked to the optical clock at $f_o = 500$ MHz is shown in Fig. 2(a) and (b), respectively. The conversion loss from the RF to the IF increases monotonically from 40 to 68 dB as the order of the phase-locked subharmonics, n, increased from $n = 1$ to 7 (see Fig. 3). These results are in agreement with (1), which shows that the conversion loss of the nth subharmonic is inversely proportional to the Bessel function $J_n\left(\frac{\pi V_{\mathrm{RF}}}{V_\pi}\right)$ and increases as the order n increases.

The single-side-band (SSB) phase noise density for different phase-locked subharmonics at an offset of 5 kHz from the



(a)



(b)

Fig. 2. Power spectrum of (a) the 7th ordersubharmonic and (b) the fractional harmonic frequency of $5f_o/3$ from the VCO phase locked to the 500-MHz frequency standard.

carrier has also been measured by using a spectrum analyzer (Tektronix 492BP) with resolution bandwidth of 100 Hz. This is also shown in Fig. 3. Note that even at the highest order of the phase locked subharmonics, the SSB phase noise is still as low as -75 dBc/Hz. In comparison, the SSB phase noise density of the frequency synthesizer modulating the laser is -95 dBc/Hz. We also find that the OEPLL system with the IOM biased at $V_\pi/4$ exhibits higher noise density than that at $3V_\pi/4$. This can be explained by the contribution to the shot noise by the term $1 + \frac{\sqrt{2}}{2}J_0\left[\frac{\pi V_{\mathrm{RF}}}{V_\pi}\right]$ for $V_{\mathrm{DC}} = V_\pi/4$ as opposed to $1 - \frac{\sqrt{2}}{2}J_0\left[\frac{\pi V_{\mathrm{RF}}}{V_\pi}\right]$ for $V_{\mathrm{DC}} = V_\pi/4$ given in (1). The phase-locking performance can be optimized by fine tuning the parameters of the loop filter. The effectiveness of

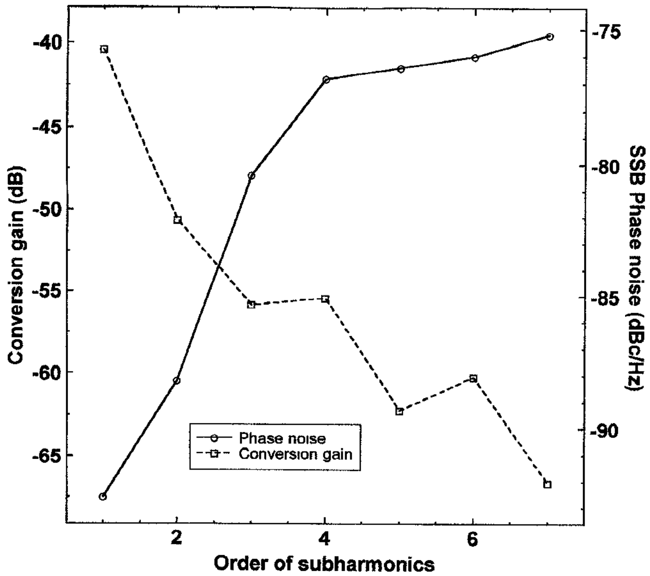


Fig. 3. The conversion loss of the phase-locked subharmonics with the IOM biased at different offset voltages (solid curve), and the signal-side-band phase noise density of the phase-locked subharmonics measured at offset frequency of 5 kHz from carrier (dashed curve).

this procedure, however, is limited by the trade-off between the noise bandwidth and phase-locking stability. Both the conversion loss and the phase noise level may be reduced by employing higher load resistance for the photodetector while incurring penalty of IF bandwidth.

The present approach is ideal for synchronization in distributed microwave architectures. Conventional electronic techniques would require a number of frequency multipliers or dividers that must be able to operate at microwave or millimeter wave frequencies. Common to other OEPLL's, the optoelectronic subharmonic technique offers the additional advantage that isolation between the LO and RF port is intrinsically perfect. An interesting new feature for the present subharmonic OEPLL is that the IOM is operated in the nonlinear regime. As a result, $nf_v \approx f_o$ can be much higher than the intrinsic bandwidth of the IOM.

V. CONCLUSION

In summary, we have proposed and demonstrated a new optoelectronic subharmonic phase-locking technique. The key component is an IOM, which is operated in the nonlinear regime and functions as an optoelectronic harmonic mixer in the laser-diode-based OEPLL. We are able to phase-lock the fractional frequencies of the optical clock at $f_o = 500$ MHz, such as $f_o/7$, $f_o/6$, $f_o/5$, $f_o/4$, $f_o/3$, $2f_o/5$, $f_o/2$, $2f_o/3$, $4f_o/3$, $3f_o/2$, and $5f_o/3$, etc.. The conversion loss of the generated nth subharmonics ($f_v = f_o/n$) ranged from 40 to 67 dB, and is inversely proportional to the Bessel function $J_n(\frac{\pi V_{RF}}{V_\pi})$. The SSB phase noise density of the optoelectronic phase locked subharmonics measured at 5 KHz offset from the carrier increases from -93 to -75 dBc/Hz as the order of the subharmonics also increases, and reaches to the background noise level (≈ -95 dBc/Hz). It is expected that an IOM with a smaller half wave voltage should improve the conversion loss and the phase-locking performance for higher-order subharmonics. In comparison with PLL's with conventional harmonic mixers, The IOM-based-OEPLL can be easily integrated with fiber-based systems and exhibits nearly ideal isolation between f_o and the subharmonics. Another potential application of the present approach is the use of the IOM as a timing discriminator for synchronization and phase control of different oscillators or pulsed lasers with different repetition rates.

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