A Laser-Diode-Based Photoconductive Harmonic Mixer for Microwave Waveform and Spectrum Measurements

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Abstract— **A laser-diode-based photoconductive harmonic mixer has been used to obtain low-frequency replicas of an optoelectronically phase-locked 12.01-GHz microwave signal as well as the waveform and spectrum of picosecond electrical pulses generated by a step recovery diode.**

I. Introduction

WAVEFORM and spectrum measurements are indispensable for the characterization of high speed electronic devices and circuits. Steady progress has been made in the past decades on conventional electronic instrumentation for these purposes, i.e., real-time and sampling oscilloscopes or the spectrum analyzer. Nonetheless, wide-band electrical probes for launching the signal into these instruments are difficult to come by. Recently, noncontact on-chip optical probing techniques, e.g., photoconductive and electrooptic sampling [1]–[3] have demonstrated bandwidth exceeding 100 GHz. For measurement of cw microwave signals with the optical methods requiring microwave sources [2], [3], it is also necessary to maintain phase coherence or time synchronization between the optical probe pulses and the microwave signal. One particularly elegant approach developed recently achieved phase-locking by intermixing the microwave signal with the picosecond laser pulse train in an electrooptical crystal (the GaAs substrate) and then displayed the waveform by photoconductive sampling via a low-frequency replica [4]. We have also implemented optoelectronic phase-locking of microwave signals up to 18 GHz using a GaAs–Cr photoconductor as the harmonic mixer in a laser-diode-based system [5]. With one gain-switched laser diode ($\lambda = 0.79$ μm) for phase-locking and another ($\lambda = 1.3$ μm) for sampling, we have also demonstrated electrooptic sampling of optoelectronically phase-locked microwave signals at 10.0 GHz [6]. In this letter, we report for the first time, the application of our laser-diode-based photoconductive sampling technique to microwave waveform and spectrum measurement via a low-frequency replica.

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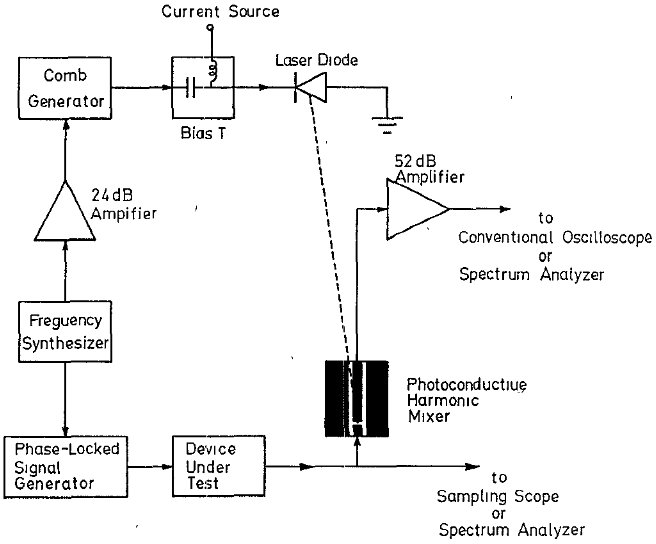

Fig. 1. Schematics of the experimental setup.

II. Experimental Method

A schematic diagram of our experimental setup is shown in Fig. 1. Two signal generators at f_{RF} and f_{LO} were phase-locked, either conventionally or optoelectronically by the photoconductive harmonic mixing technique [5], with an offset frequency Δf, $\Delta f = f_{\mathrm{RF}} - f_{\mathrm{LO}}$. One of the signal generators was used to gain-switch a diode laser (Mitsubishi, model ML-4102, $\lambda = 790$ nm) at f_{LO}, generating 30-ps optical pulses with an average power of 1 mW. The other one at f_{RF} was used to bias a photoconductive switch with a 10-μm gap in a 50-Ω coplanar waveguide transmission line fabricated on GaAs–Cr substrate. The switch functioned as a harmonic mixer. The sampling output at the intermediate frequency (IF) consists of sum and difference of multiples of f_{RF} and f_{LO}, $f_{\mathrm{IF}}(M,N) = Mf_{\mathrm{RF}} \pm Nf_{\mathrm{LO}}$, where M, N are integers. The waveform or spectrum of the baseband of $f_{\mathrm{IF}}(M,N)$ reproduces that of the microwave signal but with a time enlargement factor $f_{\mathrm{RF}}/\Delta f$. For a faithful reproduction of the signal, the number of sampling points, $L = f_{\mathrm{LO}}/\Delta f$, should be as large as possible to avoid the aliasing effect. The bandwidth of the laser pulses and the photoconductor should also be sufficient high, i.e., exceeding that of the signal. Otherwise, deconvolution of the replicated

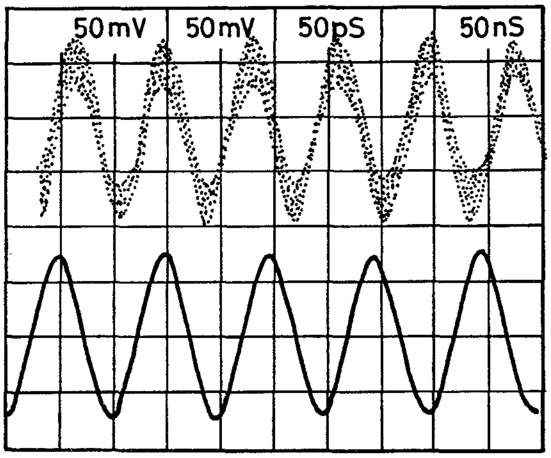

Fig. 2. Optoelectronically phase-locked 12.01-GHz microwave signal measured by a sampling oscilloscope (upper trace, vertical scale: 50 mV/div, horizontal scale: 50 ps/div) and the present technique (lower trace, vertical scale: 50 mV/div, horizontal scale: 50 ns/div).

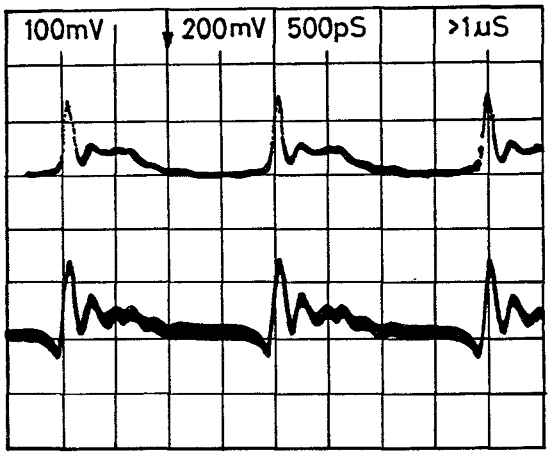

Fig. 3. Output waveform of a SRD at 499 MHz measured by a sampling oscilloscope (upper trace, vertical scale: 100 mV/div, horizontal scale: 500 ps/div) and the present technique (lower trace, vertical scale: 200 mV/div, horizontal scale: >1 μs/div).

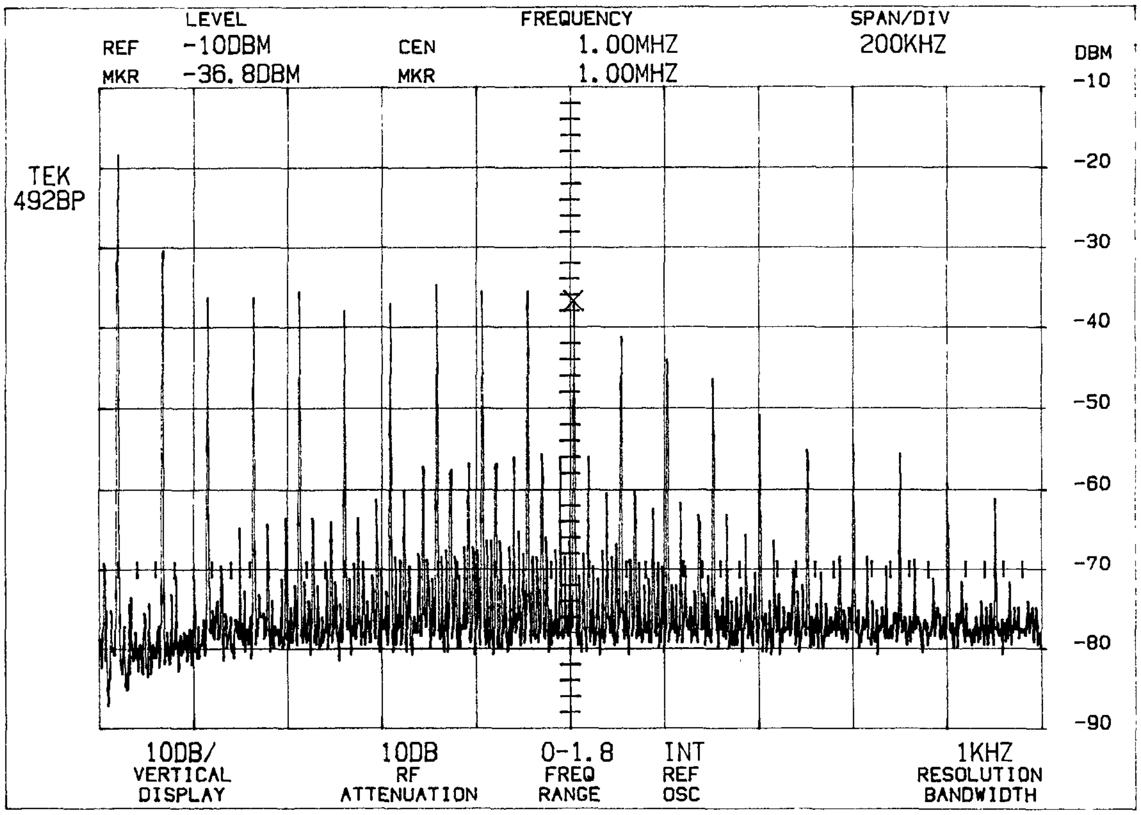

Fig. 4. Spectrum of the output of a SRD at 499 MHz measured by the present technique.

waveform or spectrum using known photoconductive response of the switch would be required. The baseband signal was low-pass filtered, amplified, and displayed on a conventional real-time oscilloscope or a spectrum analyzer.

III. Results and Discussions

In the first experiment, we have measured an optoelectronically phase-locked 12.01-GHz microwave signal [5], [6] transmitted through a short length of coaxial cable (the device under test, DUT). The waveform directly displayed on a sampling oscilloscope (Tek7854) is shown in Fig. 2 (upper trace). The down-converted 10MHz baseband IF signal displayed with real-time plug-ins on the same oscilloscope is shown in Fig. 2 (lower trace). The waveform of the lower trace reproduced that of the upper trace but with 1201-fold enlargement in time. The number of sampling points per period of the measured waveform was 50. In another experiment, we demonstrated the capability of replicating a fast electrical signal and its harmonic spectrum, a step recovery diode (SRD) was used as the DUT. A 499-MHz sinusoid electronically phase-locked to the activating laser pulse train (at 498.9 MHz) was amplified and used to drive the SRD that generated ≈100-ps-wide electrical pulses. The output of the SRD as measured directly by a sampling oscilloscope is shown in Fig. 3 (upper trace). The replicated waveform (with 4990-fold enlargement in time) is also shown in Fig. 3 (lower trace). The number of sampling points per period is 4989 in this case. This is a factor of 624 improvement over the previous work, which used a main-frame Nd–YAG laser system [4]. This is only possible because of higher and readily adjustable repetition rate of the gain-switched laser diode used as the light source. The replicated spectrum of the output of the SRD is shown in Fig. 4. For both Fig. 3 (lower trace) and Fig. 4, our data were bandwidth limited by the system, i.e., 90-ps FWHM photoconductive response of the switch as excited by 30-ps pulses from the laser diode. The fidelity of the sampled electrical waveform can be improved by using a deconvolution procedure taking into account the photoconductive response of the switch.

IV. Conclusion

In summary, we have demonstrated for the first time to our knowledge, microwave waveform and spectrum measurement via a low frequency replica using a laser-diode-based photoconductive harmonic mixer. Waveforms of optoelectronically phase-locked 12.01 GHz microwave signals as well as waveform and spectrum of picosecond electrical pulses generated by a step recovery diode measured by this technique are presented. In comparison with previous electrooptical sampling or photoconductive sampling experiments using main-frame lasers, the principal advantages of the present system are: 1) compactness, 2) a large number of sampling points, and 3) waveform and spectrum can be displayed on any convenient time scale or frequency range. With shorter laser pulses and faster photoconductive switches, we expect that on chip phase-locking and measurement of microwave waveform and spectrum up to 100GHz should be possible with this approach in the future.

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