A Novel 3.5-GHz Microwave Counter Using an Opto-Electronic Harmonic Heterodyne Technique

C. S. Chang and H. Feng Chiu

***Abstract*—A novel 3.5-GHz microwave counter using an opto-electronic harmonic heterodyne technique has been demonstrated. The system's performance has been discussed and evaluated, and is viewed as good, in comparison with today's microwave-counting systems. It is believed that this novel device has potential for measuring signals above 100 GHz.**

I. INTRODUCTION

AN ELECTRONIC counter is an instrument for measuring and calibrating the frequency of electrical signals. In many applications it is desirable and necessary to expand the detection range of counters to the microwave and millimeter wave. Conventional electronic counters are constructed by using digital logic circuits as building blocks. Their frequency range may be limited by the responded speed of the logic circuits. Normally, frequency down-conversion technique is employed when the signal to be detected has frequency above 500 MHz. Techniques such as prescaling, heterodyne conversion, transfer oscillation, and harmonic heterodyne conversion, are developed for this purpose. Among them, the technique of harmonic heterodyne conversion[1] is the most popular one used in today's microwave-counting system (i.e., HP 5350 series). Although this technique provides advantages of a comparatively simpler structure and the capability to measure signals with higher frequencies, it still suffers the same limitation in frequency measurement because the bandwidth of the sampling signal and microwave mixer are limited. For example, electrical sampling pulses generated by a comb generator are limited to a pulsewidth of 25 ps, which corresponds to a 3-dB bandwidth of ~20 GHz. In order to increase the counting range of the system, sampling pulses with shorter pulsewidths need to be used. Unlike electrical sampling, the optical-sampling technique can easily provide the capability for detecting signals with frequencies above 100 GHz, since picosecond or subpicosecond laser pulses are readily available.

In this paper, a novel technique which demonstrates harmonic heterodyne down-conversion by opto-electronic means is reported. It utilizes short optical pulses as the sampling signal and an ultrafast photoconductor as the opto-electronic harmonic mixer in the microwave-counting system. The authors believe that counters based on this principle have the potential to detect signals up to 100 GHz.

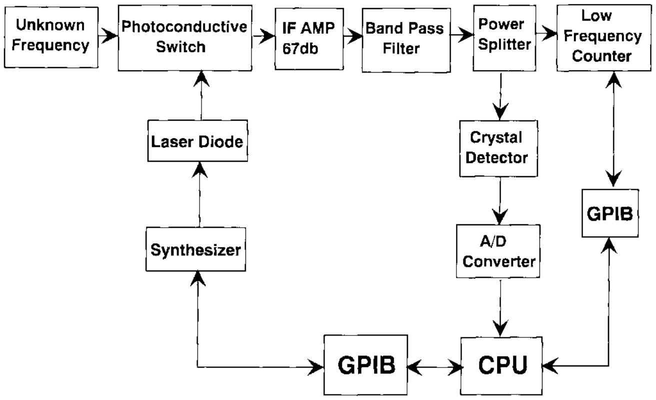

Fig. 1. Block diagram of the microwave counter using an opto-electronic harmonic heterodyne technique.

There are two commonly used techniques for optical sampling: electro-optic sampling [1], [2] and photoconductive sampling [3]. Recently, several groups have successfully shown that both electro-optical sampling [4]–[6] and photoconductive sampling [8] techniques can be applied to intermix harmonics frequency of the repetitive optical pulses with microwave signals in opto-electronic harmonic mixers for phase-locking applications [4], [5], [7], waveform measurement [8], [9], and timing synchronization [10], [11]. It is interesting to investigate the feasibility of using photoconductive sampling techniques for frequency measurement.

II. THE OPTO-ELECTRONIC HARMONIC HETERODYNE TECHNIQUE

Fig. 1 is a block diagram of a microwave counter using the opto-electronic harmonic heterodyne technique. This system configuration is similar to that reported previously [12]. In Fig. 1, instead of driving a comb generator to generate short electrical pulses (as in a conventional microwave counter), a frequency synthesizer is used to drive a gain-switched semiconductor diode laser, which produced a series of short optical pulses as the sampling signals. Frequency down-conversion is achieved by frequency intermixing between the input unknown signal and the sampling signal in a photoconductor. The desired IF, f_{If}, was amplified by an IF amplifier with a power gain of 67 dB and selected by a bandpass filter (10–90

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The authors are with the Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, R.O.C.

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[1] "Fundamentals of microwave frequency counters," HP Application Note 200-1.

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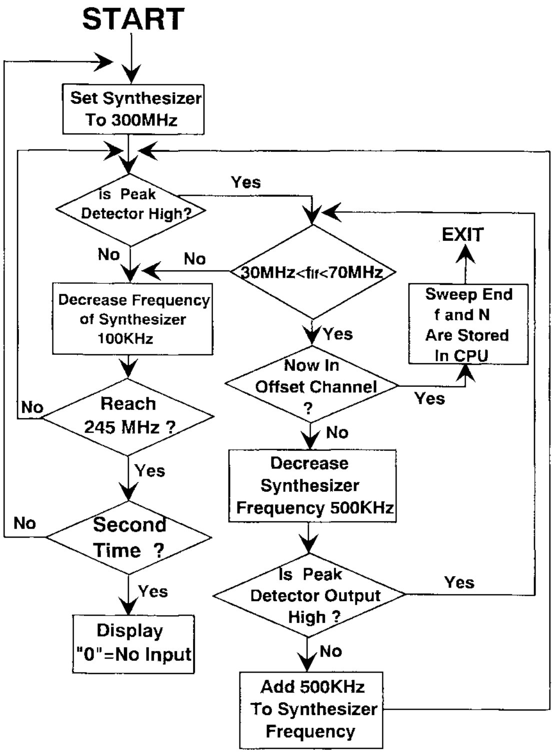


Fig. 2. System flowchart of the counter.

MHz), and then directly detected by a low-frequency counter. The programmable frequency synthesizer was controlled by a central processing unit (CPU) and decreased in frequency until one $f_{\rm If}$ was in the counting range of the low-frequency counter. A crystal detector was set for measuring the amplitude of the input signal and governing the starting time for detection in a low-frequency counter. The unknown frequency f_x can be defined by

$$f_x = Nf \pm f_{\rm If} \tag{1}$$

where N (> 1) is the number of harmonics of the sampling pulses and f is the repetitive frequency of the sampling pulses, which is exactly the same as the programmed RF frequency of the frequency synthesizer. In order to determine the variable N and sign $(\pm)$, two similar equations are required. This can be done by means of varying the frequency synthesizer from its previous value by a small amount of Δf. Thus, $f_2 = f_1 - \Delta f$ and $f_x = Nf_1 \pm f_{{\rm If}_1} = Nf_2 \pm f_{{\rm If}_2}$. As a result, the number N can be expressed as

$$N = \left| \frac{f_{{\rm If}_1} - f_{{\rm If}_2}}{f_1 - f_2} \right| = \frac{|f_{{\rm If}_1} - f_{{\rm If}_2}|}{\Delta f}. \tag{2}$$

Assuming that $f_{{\rm If}_1} > f_{{\rm If}_2}$, then $f_x = Nf_1 - f_{{\rm If}_1}$. Otherwise, $f_x = Nf_1 + f_{{\rm If}_1}$. Fig. 2 represents the system flowchart of this configuration. In this structure, the programmed RF frequency of the frequency synthesizer was swept from 300 to 245 MHz. The frequency f was lessened every step by 100 kHz until the $f_{\rm If}$ was moved within the frequency range between 30 and 70 MHz. Δf was set at 500 kHz.

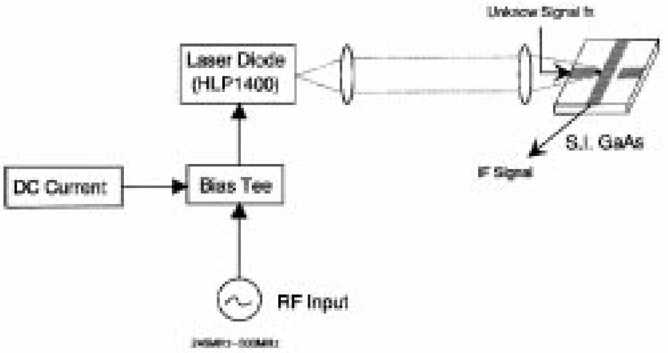


Fig. 3. Schematics of the experimental setup for opto-electronic harmonic heterodyne down-conversion.

III. OPTO-ELECTRONIC HARMONIC HETERODYNE EXPERIMENT

A schematic diagram of the authors' experimental setup for opto-electronic harmonic heterodyne is depicted in Fig. 3. The repetitive optical pulses were generated by a gain-switched laser diode (Hitachi, model HLP 1400) with a wavelength of 0.81 μm. The opto-electronic harmonic mixing was carried out in a semi-insulated (SI) GaAs photoconductor. The photoconductor was designed and fabricated with two crossed 50-Ω microstrip lines, which are separated by a gap of 20 μm between them. The input unknown signal to be measured was connected to one end of the line. The short optical sampling pulses were directed onto the gap of the photoconductor to intermix with the input microwave signal. The down converted signal $f_{\rm If}$ was produced and transmitted to the end of another transmission line.

In this paper's system, a dc current of 22 mA and both synthesized and amplified RF signals (with power of 25 dBm) were supplied to the laser diode, a train of short optical pulses with a full width at half maximum (FWHM) of 65 ps and an average power of 0.74 mW (peak power of 10.8 mW) were generated and directed to illuminate the active region of the photoconductor. A 10-dBm continuous-wave (CW) signal with frequency of 3.05 GHz was used as the test signal and applied to the SI–GaAs photoconductor. The down-converted $f_{\rm If}$ amplified by several cascaded amplifiers with a total gain of 67 dB was observed by a spectrum analyzer (TEK 492P). As expected, $f_{\rm If} = 50$ MHz (shown in Fig. 4) is found at the output by mixing the test signal with the 12th harmonic of the laser pulses at 250 MHz (that is, 50 MHz $= 3050 - 12 \cdot 250$ MHz).

During this part of the experiment it is important to keep each harmonics' amplitude of the sampling signal constant when the driving RF frequency is tuned. If the harmonics' constant amplitude cannot be maintained, the measurement of the frequency, the amplitude of the down-converted frequency $f_{\rm If}$, as well as the unknown input signal f_x, may fall into a undetected range or misleading situation. Of course, using a large amount of data storage in the CPU unit for the amplitude calibration can solve this problem. However, this will make the system more complicated to operate. Using the opto-electronic harmonic heterodyne technique, as compared to the conventional electronic harmonic heterodyne, has another advantage

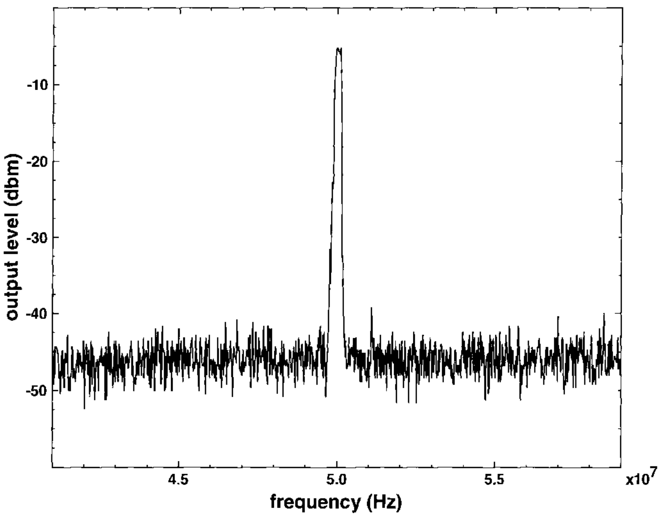
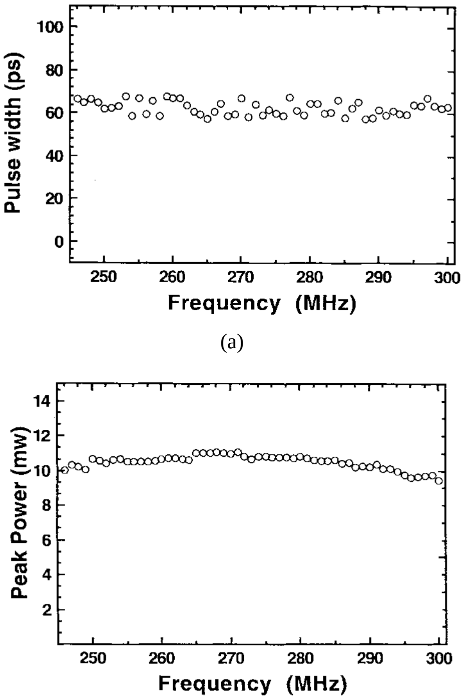


Fig. 4. The signal of a mixed intermediate frequency measured by a spectrum analyzer (TEK492P). The center frequency is 50 MHz, frequency span is 1 MHz/div.



(a)

(b)

Fig. 5. Variation of (a) pulsewidth and (b) peak power of the optical pulses generated by a gain-switched laser diode as the RF frequency is tuned from 300 to 245 MHz.

of obtaining the constant harmonics' amplitude of the sampling signal. This will be a problem for today's microwave counter because it is very difficult to obtain the electrical pulses from a comb generator with a constant pulsewidth and pulseheight over a wide RF-frequency range. Fig. 5(a) and 5(b) shows that constant optical pulsewidth and pulseheight (as well as the peak power) from a laser diode are achieved as the RF frequency is tuned from 300 to 245 MHz. A wider RF frequency tuning range will also provide a wider counting range for the counter according to the calculation of $N_{\max}$ [see (1)] from [13]. This will be easily obtained in an optical system.

IV. SYSTEM PERFORMANCE AND DISCUSSION

The performance in this paper's microwave-counting system, such as counting range, frequency accuracy, stability, and modulation tolerance, will now be discussed.

The counting range of this paper's system is decided by the same factors as that of a conventional microwave-counting system. It is primarily determined by the pulsewidth of the sampling signal and frequency response of the mixer. The pulsewidth of the optical pulses is 65 ps. The frequency response of the photoconductor was measured by observing the variation of the amplitude of the mixed-frequency signal. The experimental setup is the same as that shown in Fig. 3, except that the RF frequency is fixed at 250 MHz and the microwave input is designated and swept over different frequencies. The 3-dB bandwidth of the photoconductor was measured to be 3.5 GHz, which is similar to that reported in [14]. The pulsewidth of the optical pulses, frequency response of the photoconductor, and counting range of this paper's system is thus limited by the 3.5-GHz bandwidth of the photoconductor.

However, a gain-switched semiconductor laser diode through solution compression in the fiber has been reported to have the capability of obtaining short optical pulses with a pulsewidth less then 1 ps and energy close to 20 pJ per pulse [15], [16]. The carrier lifetime of the photoconductor has also been reported to be less than 1 ps in low-temperature moleculer-beam-epitaxy-grown (MBE) material [17]. By improving both optical pulsewidth and the frequency response of the photoconductor, this system has the potential to detect microwave signals of frequencies above 100 GHz.

The accuracy of frequency was tested by using a calibrated 1-GHz frequency synthesizer (HP 8662A). The results (see Fig. 6) show some observable errors in the tested signals. The error frequency $\Delta f_x = N\Delta f_1 + \Delta f_{\mathrm{If}_1}$, where Δf_1 ($\sim$1.5 Hz) and Δf_{If_1} ($\sim$2 Hz), are due to the variation from the RF-frequency synthesizer (Anristu, MG 545A3) and the low-frequency counter (Iwatsu, SC-7104), respectively. No obvious evidence is shown in the system which indicates that the error is generated optically. It is thus concluded that the accuracy of frequency in the authors' system is compatible with that of any conventional microwave-counting systems.

The stability of this counter has also been examined after 2-h, 4-h, and 8-h periods of time. This structure shows a good stability in time regardless of when the frequency and its amplitude of the unknown signals are investigated.

The sensitivity will strongly depends on the conversion loss during the process of frequency down-conversion. The power of the signal obtained at the mixed frequency f_{If} was measured to be lower than the power of the input microwave by 81 dB. However, an amplifier with a gain of 67 dB managed to decrease this power loss to 14 dB. If any signal under detection is weak, the enhancement of the sensitivity needs to be considered. This problem can be softened by shortening the gap distance of the photoconductor and increasing the output power from the laser diode. The minimum detectable power for the low-frequency counter is -13 dBm, which regulates the minimum power for an input microwave at about $+1$ dBm.

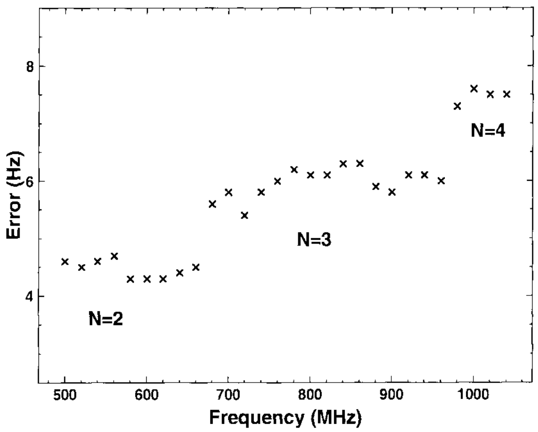


Fig. 6. The error frequency observed in our microwave counter.

In this paper's system, the frequency range of the desired IF, $f_{\rm IF}$, was set between 30 and 70 MHz. Signals picked up by the bandpass filter were from 10 to 90 MHz—which is a difference of ±20 MHz between these frequency ranges. In other words, this paper's system is designed to allow the input signal from having a modulation tolerance of ±20 MHz. This value can be adjusted by replacing the passband from the filter.

V. CONCLUSION

A microwave counter based on the technique of opto-electronic harmonic heterodyne has been developed. Due to the limited bandwidth of the presently used photoconductor, the counter only demonstrates measurement of a frequency signal close to 3.5 GHz. The counting range of the system can be expanded if both the pulsewidth of the optical pulses and carrier lifetime of the photoconductor were shortened. The system provides the potential to measure the signal with frequency above 100 GHz. The accuracy of frequency is compatible to that of today's microwave counters. The stability is good and the modulation tolerance is about ±20 MHz. Except for the sensitivity of the system, its performance compares well to the conventional system.

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