High-Power Photonic Microwave Generation at K- and Ku-Bands using a Uni-Traveling-Carrier Photodiode

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***Abstract* — A K- to Ka-band photonic microwave generator (PMG) consisting of a uni-traveling-carrier photodiode (UTC-PD) and a monolithically integrated bias circuit utilizing a 1/4-wavelength coplanar waveguide is presented. The device exhibits a high saturation-output-power of +14 dBm at 26 GHz for a bias voltage of -4 V. The output power is almost constant within a frequency range from 23 to 29 GHz. The 3-dB down bandwidth of the generator is as wide as 20 GHz, which is in good agreement with the circuit model calculation. Two types of devices, one with and without a DC-cut capacitor, exhibit almost the same input-output characteristics. The PMG is a suitable device for the broadband high-output fiber-radio applications.**

I. Introduction

The growing demand for expanding data throughput in wireless communication system has been accelerating the use of frequencies up to the millimeter-wave (mm-wave) range. In such a high frequency range, weather-related attenuation is a concern, even in relatively short-range links. Thus, for constructing high-throughput and relatively long-range systems such as fixed wireless access (FWA) systems [1] and wireless trunk lines, the K- and Ka-bands are the most appropriate.

As the frequency becomes higher, the electrical transmission of the microwave/mm-wave signal from the central station to the base station becomes more difficult. One approach to overcoming this problem is to use microwave/mm-wave photonics (fiber-radio) technology, which can solve the large loss problem in microwave/mm-wave electrical transmission. In addition, the use of a high-output-power photodiode (PD) can eliminate the costly post amplification circuit and simplify the base station. The uni-traveling-carrier photodiode (UTC-PD) [2] is one of the best solutions for such purposes, because it provides a high 3-dB bandwidth (f_{3dB}) and a high-saturation-output power simultaneously. To date, an f_{3dB} of 310 GHz [3] and an output power of +12 dBm at 60 GHz [4] have been demonstrated. Another concern is the costly external bias-tee circuit, which is usually used for supplying a DC power to a PD. Thus, for practical applications, it is also necessary to monolithically integrate a bias circuit with a photodiode without significantly sacrificing chip area or increasing device fabrication cost.

In the present work, we have fabricated a photonic microwave generator (PMG) by monolithically integrating a UTC-PD and a bias circuit designed for operation at 26 GHz.

II. Circuit Configuration And Device Fabrication

Figure 1 shows the circuit diagram and Fig. 2 shows micrographs of the fabricated PMGs, PMG-A and PMG-B. The circuit consists of a UTC-PD and a short-stub bias circuit [5] containing a 1/4-wavelength (1/4-λ) coplanar waveguide (CPW) and a metal-insulator-metal capacitor (6.4 pF). The length of the CPW is designed to be 1150 μm for operation at 26 GHz. PMG-B has an additional DC-cut capacitor (1.8 pF) in the output CPW in order to make the electrical connection to the external circuit more flexible. The chip size of each device is 600 × 800 μm^2. Because the widely used spiral inductor usually requires a large device area, additional process steps, and a design optimization, we consider this CPW bias circuit to be superior for narrow-band applications. As seen in Fig. 2, the 1/4-λ CPW bias circuit is set within our standard-sized PD chip.

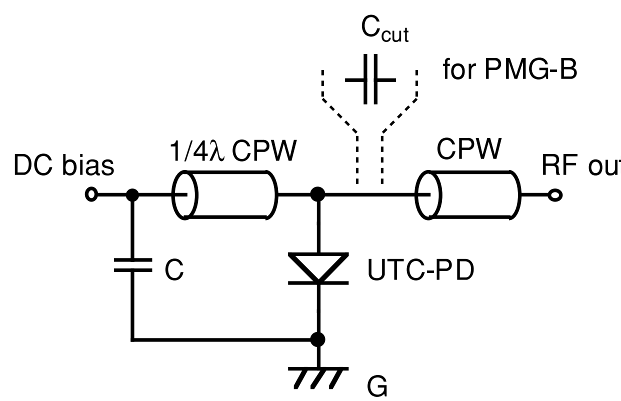
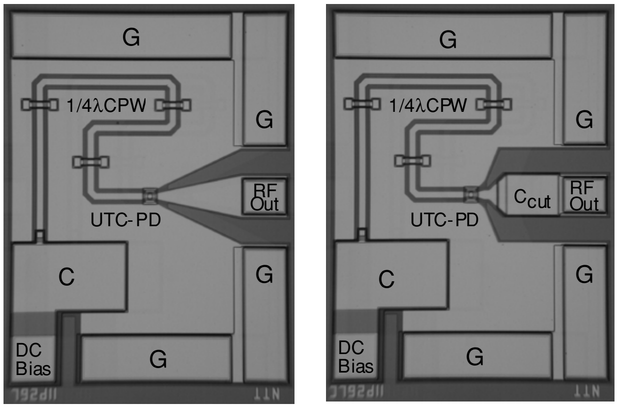


Fig. 1. Circuit diagram of the PMGs, PMG-A and PMG-B.



PMG-A PMG-B

Fig. 2. Micrograph of the fabricated PMGs.

The epi-layers were grown by low-pressure MOCVD. The absorption layer consists of p-InGaAs layers (p = 1, 4.5 and 20 × 10^{17} /cm^3, total 4700 A), and the collection layer consists of an i-InGaAsP layer (100 A) and i/n/i-InP multi-layers (total 3030 A). Double-mesa back-illuminated UTC-PDs with an absorption area of 99 μm^2 were fabricated by wet chemical etching and metal-lift-off processes. Each device was integrated with 50-Ω coplanar lines (one for the output, one for the 1/4-wavelength short-stub) on the semi-insulating InP substrate. These elements were monolithically integrated without employing an additional process step in the standard UTC-PD process. The backside of the substrate was mirror-polished and anti-reflection coated after the devices were fabricated. The responsivity measured in a broad-area device at λ = 1.55 μm was 0.45 A/W.

III. CHARACTERIZATION

The fabricated devices were characterized on-wafer using a cascade probe in two ways. A small-signal frequency response was measured using a lightwave component analyzer (HP-83467C) up to 50 GHz. A CW light (λ = 1.55 μm) was combined with the small-signal light from the analyzer in order to evaluate the response at higher photocurrents. The microwave output characteristic, on the other hand, was measured using the setup shown in Fig. 3. Here, a CW light from a distributed feedback laser diode (DFB-LD) was modulated by a $LiNbO_3$ Mach-Zehnder modulator (LN-MZM) in order to generate the subcarrier multiplexed (SCM) light signal. The LN-MZM was biased at the transition null point and driven by an electrical signal with half the desired frequency. The optical modulation index was about 0.9 throughout the experiment. The SCM light was then amplified using EDFA and focused onto the UTC-PD through an object lens from the backside of the wafer. The generated microwave power was measured using a spectrum analyzer.

VI. EXPERIMENTAL RESULTS

Figure 4 shows the dependence of the f_{3dB} of a UTC-PD without a bias circuit on the average photocurrent (I_p) at a bias voltage (V_b) of -3 V. These f_{3dB} values were estimated from the small-signal frequency responses. The f_{3dB} exceeds 50 GHz except in the very low and very high photocurrent regions, where we could not determine the actual f_{3dB} value due to the frequency range limitation of the analyzer. The lower f_{3dB} in the low photocurrent region is attributed to the less effective self-induced field in the absorption layer at low excitation [6], while the decreased f_{3dB} in the high photocurrent region is due to the output current saturation caused by the space charge effect in the depletion region of the collection layer. These results confirm that the fabricated UTC-PD has a sufficiently high bandwidth for use at around 26 GHz in a wide photocurrent range.

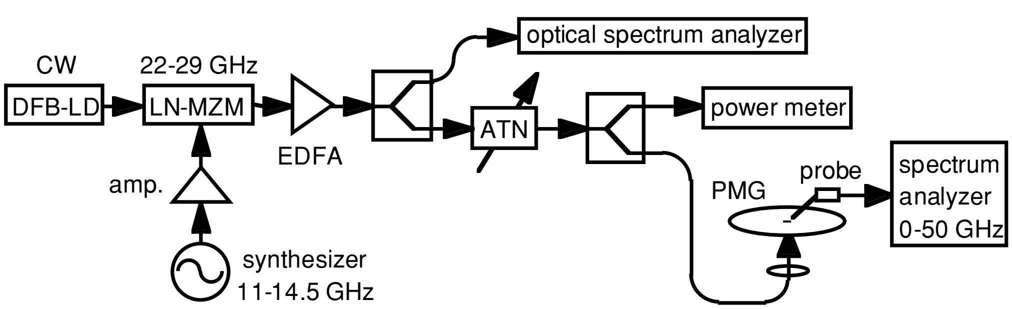


Fig. 3. Experimental setup for the output microwave power measurement.

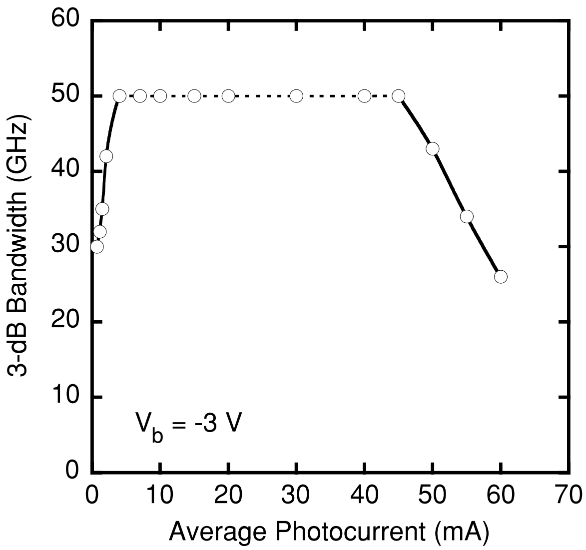


Fig. 4. Relationship between 3-dB bandwidth and average photocurrent for a UTC-PD without a bias circuit.

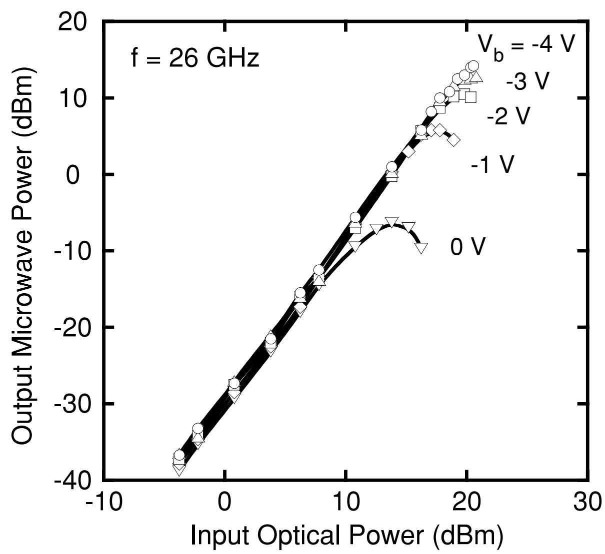


Fig. 5. Relationship between input optical power and output microwave power in PMG-A at 26 GHz.

Figure 5 shows the relationship between the microwave output power and the input optical power (P_{in}) for PMG-A at 26 GHz for several bias voltages. A wide linearity range of the output power against the photocurrent is seen for each bias condition. The saturated output power was increased from -6 to +14 dBm by increasing V_b from 0 V to -4 V. To our knowledge, this is the highest saturated-output-power directly generated from a PD at frequencies above K-band.

Figure 6 shows the dependence of output microwave power on frequency at several optical input powers for V_b of -3 V. As seen in this figure, the output power depends very weakly on the frequency, indicating that one PMG can be simultaneously used at several carrier frequencies.

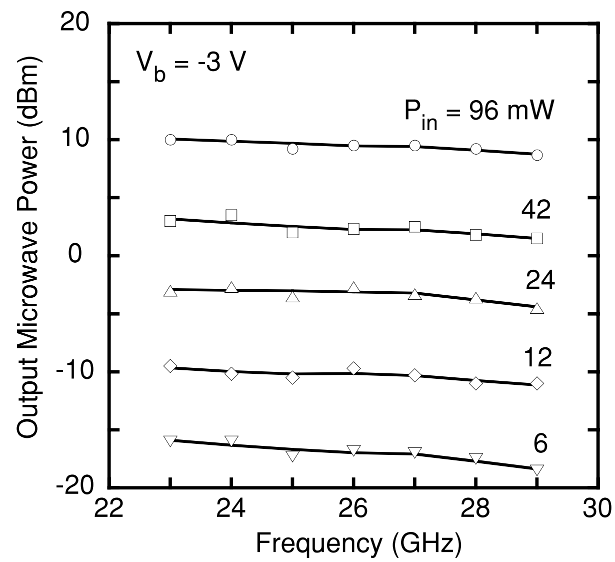


Fig. 6. Dependence of output microwave power on frequency in PMG-A at several optical input powers.

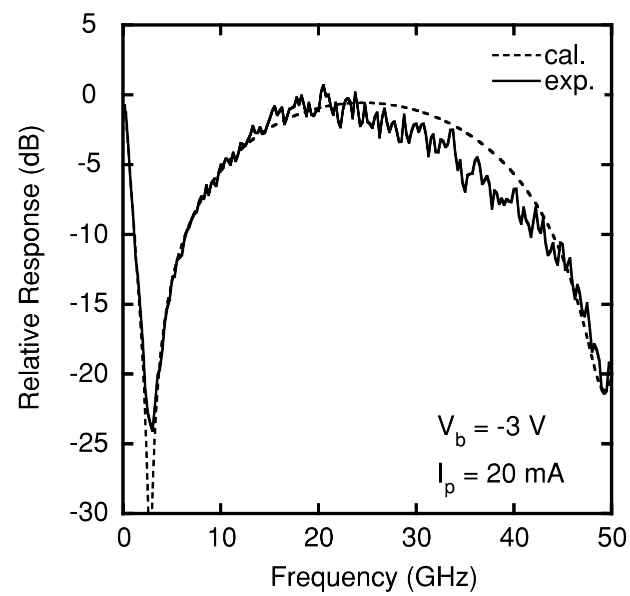


Fig. 7. Small-signal frequency response of PMG-A.

Figure 7 shows the small-signal frequency response of PMG-A at I_p of 20 mA and V_b of -3 V. The broken line in the figure is the analytical calculation based on a simple circuit model. The experimental result agrees well with the calculation, indicating that the characteristics of the CPW bias circuit are well predicted by such a basic model calculation. In this calculation, the group velocity of the propagating signal is optimized to be 1.13×10^{10} cm/s, which is slightly smaller than the value used in the initial circuit design (1.2×10^{10} cm/s). The 3-dB bandwidth of the PMGs are as wide as 20 GHz, which covers commercially used frequencies for FWA and local multipoint distribution systems such as 22, 24, 26, and 28 GHz bands [1], [7].

Figure 8 compares the relationships between the microwave output power and the input optical power for a UTC-PD with an external (no internal) bias-tee circuit, PMG-A, and PMG-B at 26 GHz for V_b of -3 V. The input-output characteristics for each device are quite similar, indicating that the introduction of the CPW bias circuit nor the DC-cut capacitor does not deteriorate the linearity and output characteristics of the PMGs. These results clearly demonstrate that the combination of a UTC-PD with a CPW bias circuit provides a practical optical-to-microwave signal-conversion device without the need for any post amplification circuit.

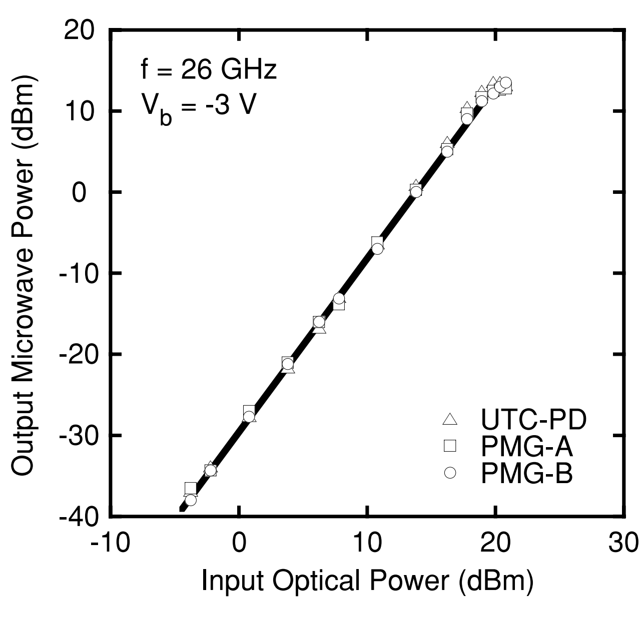


Fig. 8. Comparison of the output characteristics for a UTC-PD without the bias circuit, PMG-A, and PMG-B as a function of input optical power.

V. Conclusion

We have fabricated a photonic microwave generator consisting of a UTC-PD and a 1/4-wavelength coplanar waveguide as a bias circuit designed for operation at 26 GHz. The fabricated PMG exhibits a high saturated-output-power of up to +14 dBm with a wide linearity at 26 GHz. It also has a very wide bandwidth of over 20 GHz ranging from Ku- to Ka-bands, indicating a capability to simultaneously use at various carrier frequencies. The influence of the bias circuit and DC-cut capacitor integration on the output characteristics is negligible. These results indicate that the PMG is a promising device that will make base stations in fiber-radio systems simple, compact, and cost-effective.

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