High-Power High-Frequency Traveling-Wave Heterojunction Phototransistors with Integrated Polyimide Waveguide

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***Abstract*— A high-power high-speed phototransistor has been demonstrated using a traveling-wave (TW) structure with an integrated polyimide optical waveguide. In our configuration, optical power transfer is distributed along the length of the device via leaky mode coupling of light from the polyimide waveguide to the active region of the phototransistor. The TW electrode design allows for an electrically long structure while maintaining high bandwidths. Due to the increased absorption volume, the optical power handling capabilities of the TW-heterojunction phototransistors (TW-HPT's) are improved over that of conventional lumped-element HPT detectors. The experimental results show no saturation of the fundamental at 60 GHz up to 50 mA of dc photocurrent.**

I. Introduction

One of the major commercial incentives driving research in photonics is the microwave fiber optic link. A typical link consists of a laser source, an external modulator, the fiber optic transmission medium, and an optical detector. High-frequency optical detectors are one of the primary components that dictate the system performance of the fiber optic link. In order to reduce the radio frequency (RF) insertion loss, increase the spurious free dynamic range, and increase the signal-to-noise ratio of the link, the photodetector needs to be able to handle high optical powers [1]. Heterojunction phototransistors (HPT's) which exhibit optical gain via transistor action offer improvements in link gain over p-i-n or MSM photodiodes. Although much work has been done on high-speed phototransistors [2], a classic design conflict exists between the simultaneous optimization of high-frequency performance and optical coupling efficiency. In lumped-element HPT's, the devices need to be scaled down in size for high-speed operation. These small devices tend to saturate at low input optical power levels because of the small absorption volume.

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In an attempt to overcome these problems, we propose to utilize the traveling-wave (TW) concepts that have been implemented so successfully in optical modulator technology and extend these concepts to HPT detectors. A schematic diagram of our TW heterojunction phototransistor (TW-HPT) is shown in Fig. 1. In our approach, we define a leaky-mode polyimide waveguide on top of the active region of the HPT. Intensity-modulated light is coupled to the polyimide waveguide and leaks into the HPT's active region along the length of the device due to the fact that the index of refraction of the semiconductor is higher than that of the polyimide. The metal pads of the HPT are coplanar waveguide with the center line contacting the emitter and the ground plane contacting the collector. The base is floating. A microwave signal is generated on the transmission line as light is absorbed along the length of the detector. The ultimate bandwidth limitation of such a device is based on the velocity mismatch between the optical wave and the induced electrical microwave [3]–[6].

Due to the integration of the polyimide waveguide and the HPT in the TW configuration, power saturation effects are improved because the absorption of the incident light signal is distributed along the entire length of the device. The layer structure for the TW-HPT is a typical HBT design consisting of a 600-Å base with a graded base–emitter junction [7]. The polyimide optical waveguide is defined on top of the emitter and lies in the gap between the center electrode and the ground plane. Since the core size for single mode fiber at an optical wavelength of 1.3 μm is approximately 9 μm, we chose the dimensions of the polyimide waveguide to be 10 $\times$ 10 μm. A second set of devices was also fabricated in which the center electrode shorted the emitter to the base to form a diode structure. We will refer to this device as TW-Diode. The optical absorption interaction length between the waveguide and the HPT device was varied from 20, 200, to 2000 μm.

II. Experimental Results

The dc optical responses of the TW-HPT and TW-Diode are shown in Fig. 2(a) and (b), respectively. A bias voltage of $V_{ce} = 1.5$ V was applied to all devices. Comparing the two figures, it is evident that the transistor action of the TW-HPT dramatically increases the sensitivity of the optical response. The optical gain G is as high as 13.5 for the 2-mm-long TW-HPT as opposed to $G = 0.374$ for the diode. For a given

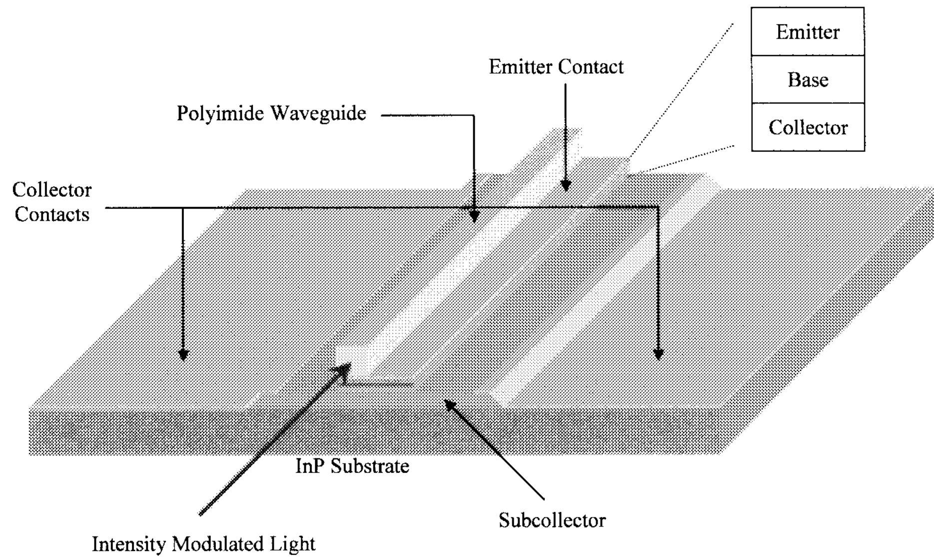

Fig. 1. Schematic diagram of the TW-HPT. Polyimide waveguide is defined on top of the active region of an HPT. The HPT's electrodes are coplanar waveguide with a characteristic impedance of 50 Ω.

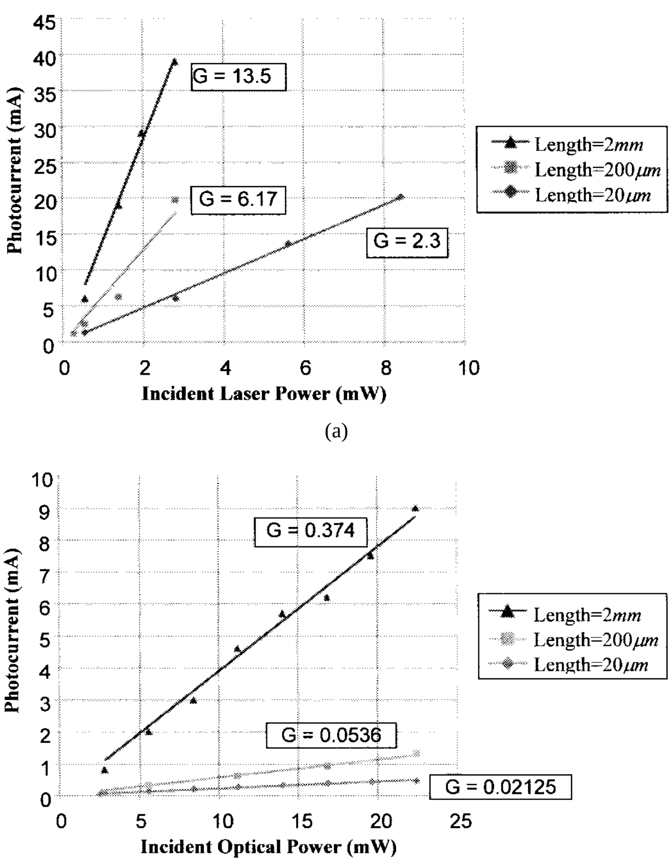

Fig. 2. DC optical response of the (a) TW-HPT and (b) TW-Diode.

optical power of 2.8 mW, the 2-mm-long diode photocurrent is 0.8 mA, but the corresponding transistor photocurrent is 40 mA, which is 50 times larger. In all cases the induced photocurrent increases linearly with increasing optical power indicating that the devices are not saturating.

By measuring the photocurrent as a function of device length for a given optical power, we can estimate the input

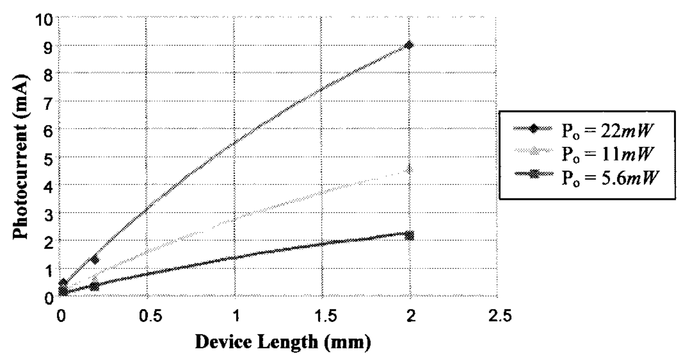

Fig. 3. Photocurrent as a function of TW-Diode device length for three different incident optical powers. The solid lines are the theoretical fit to the data.

optical coupling efficiency. This is most easily accomplished with the diode since the transistor gain can vary from device to device. The results for the TW-Diode are shown in Fig. 3 for three different input optical powers. The solid lines are a theoretical fit to the measured data based on the equation

$$I_{ph} = \frac{q\eta}{h\nu} P_o. \tag{1}$$

I_{ph} is the optically generated portion of the output current, P_o is the incident optical power, q is the electronic charge, $h\nu$ is the energy of the incident photons, and η is the external quantum efficiency. The external quantum efficiency can be broken up into separate factors that describe the different mechanisms for light loss and light absorption:

$$\eta = \eta_{\text{coupling}} \cdot \eta_{\text{propagation}} \cdot \eta_{\text{leaky}} \tag{2}$$

where η_{coupling} is the input coupling loss between the optical fiber and the polyimide waveguide, $\eta_{\text{propagation}}$ is the propagation loss from the optical input of the device to the active region, and η_{leaky} is the amount of light absorption that occurs in the active region via the leaky mode coupling mechanism. $\eta_{\text{propagation}}$ is difficult to estimate so we will

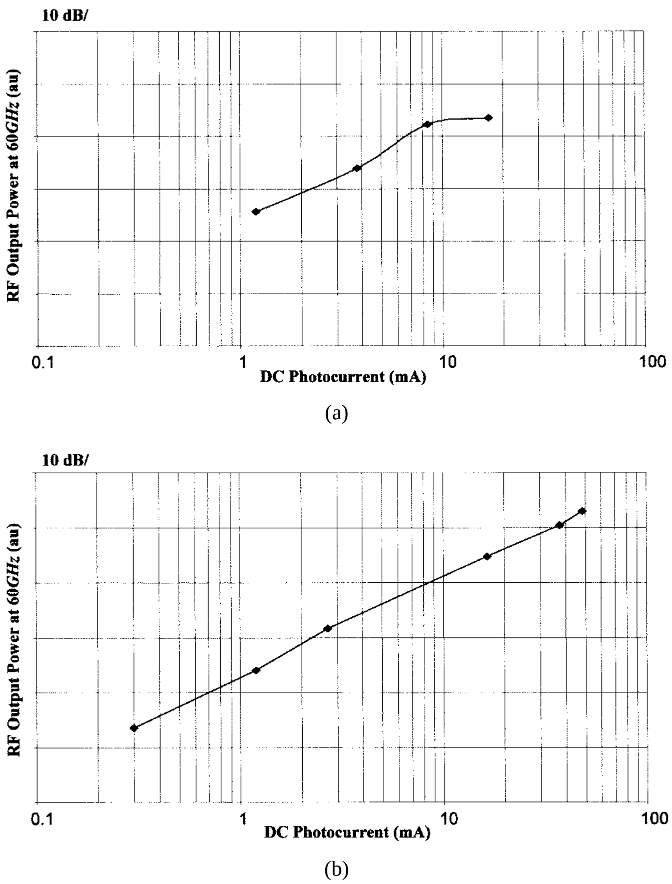

Fig. 4. Optical power saturation at 60 GHz for (a) lumped-element HPT and (b) 200-μm-long TW-HPT.

combine $\eta_{\text{propagation}}$ with η_{coupling} and define this as the total input coupling loss prior to the active region of the device. η_{leaky} can be written mathematically as

$$\eta_{\text{leaky}} = 1 - e^{-\alpha_{op} l} \tag{3}$$

where α_{op} is the effective absorption coefficient which is determined by the thickness of the polyimide waveguide and l is the length of the active region. Plugging in (2) and (3) into (1) we obtain

$$(I_{ph} = \frac{qP_o}{h\nu}\, \eta_{\text{coupling}}(1 - e^{-\alpha_{op} l}). \tag{4}$$

Given that our polyimide waveguide thickness was measured to be 7.5 μm, the effective optical absorption coefficient given by our previously published simulations is taken to be $\alpha_{op} = 4$ cm^{-1} [7]. We can now fit (4) to the measured data of the 20-μm-, 200-μm-, and 2-mm-long TW-Diodes as shown in Fig. 3 and determine our input coupling efficiency to be $\eta_{\text{coupling}} = 70\%$.

The optical power saturation measurements for the TW-HPT's were made at 60 GHz using two diode-pumped Nd : YAG lasers in an optical mixing configuration at a wavelength of 1.3 μm. The results are presented for the 200-μm-long device since this seemed to exhibit the best trade-off between device length and performance. The results for the TW-HPT were compared to a lumped-element HPT that was fabricated with a similar layer structure and had an emitter area of 8 $\times$ 8 μm. The displayed data in Fig. 4 shows that the lumped-element HPT output signal begins to saturate at a dc photocurrent of 8 mA whereas the 200-μm-long TW-HPT shows no signs of saturation up to 50 mA. The power-handling ability of the TW-HPT is superior to that of the lumped-element HPT due to the distributed nature of the optical absorption via the leaky mode configuration.

III. Conclusion

We experimentally measured the optical response of the TW-HPT and demonstrated high optical gains with input optical coupling efficiencies of 70%. A 200-μm-long TW-HPT exhibited no output power saturation up to 50 mA of dc photocurrent at an operating frequency of 60 GHz. We envision widespread applications of the high-power high-frequency TW-HPT in future photonic and optoelectronic integrated circuits.

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