Velocity-Matched Distributed Photodetectors with High-Saturation Power and Large Bandwidth

L. Y. Lin, *Member, IEEE,* M. C. Wu, *Member, IEEE,* T. Itoh, *Fellow, IEEE,*
T. A. Vang, R. E. Muller, D. L. Sivco, and A. Y. Cho, *Fellow, IEEE*

***Abstract*— A high-power, high-bandwidth photodetector is experimentally demonstrated using a novel velocity-matched distributed photodetector (VMDP). The distributed photodetector structure can achieve large absorption volume and high-saturation power while maintaining the high-speed performance of the fast photodiodes. The VMDP with 56 mA saturation photocurrent and an instrument-limited 3-dB bandwidth of 49 GHz is achieved. The results show that VMDP is ideal for high-performance microwave fiber-optic links and high-power optical-microwave applications.**

I. Introduction

HIGH-POWER, high-frequency photodetectors are the key components in microwave fiber optic links to reduce RF insertion loss, and increase spurious free dynamic range and signal-to-noise ratio [1]. They are also important for optical heterodyned receivers and optoelectronic generation of high-power microwaves and millimeter-waves. Though significant progress has been made in high-speed photodetectors [2]–[6], these photodetectors have very low saturation power because of the small absorption volume (on the order of 1 μm^3) required to achieve high-speed operation. Since the dominant saturation mechanism in photodetectors is the electric field screening effect caused by the photo-generated carriers under intense illumination, the most direct way to increase the saturation power is enlarging the effective absorption volume. The saturation phenomena in p-i-n photodetectors has been studied [7]. Large core waveguide photodetector has been proposed to increase the saturation power, however, at the expense of its bandwidth because longer detector length is required [8]. Velocity-matched traveling wave photodetectors, first suggested by [9], have been proposed to further increase the absorption volume [10]. However, very low bandwidth (4.8 GHz) was reported because of the difficulty to combine velocity-matched microwave transmission line with photodiodes [10].

Previously, we have proposed a velocity-matched distributed photodetector (VMDP) to increase the optical saturation power without sacrificing its bandwidth or efficiency. The VMDP consists of an array of small photodiodes serially connected by a passive optical waveguide, and the photocurrents are collected by a *separate output microwave transmission line* that is velocity-matched to the optical waveguide and has an impedance of 50 Ω [11]. One unique advantage of the VMDP is that the optical waveguide, photodiodes, and microwave transmission line can be independently optimized. Velocity-matched 50 Ω transmission line can be implemented without sacrificing the photodiode performance. The photodiodes are kept below saturation by coupling only a small portion of light from the passive waveguide [12].

In this letter, we report on the experimental demonstration of the high-power, high-frequency VMDP with nanoscale MSM photodiodes. A very-high-peak saturation photocurrent of 56 mA (at 1-dB compression of quantum efficiency) and a 3-dB bandwidth of 49 GHz are achieved. The measured bandwidth is limited by our current measuring instrument.

II. Device and Fabrication

The schematic structure of the VMDP is shown in Fig. 1(a). Nanoscale MSM diodes are chosen as the active photodiodes because of their low parasitics and the ease of integration with the microwave transmission lines. It should be noted that the VMDP concept can be applied to other photodiodes such as p-i-n. A 50-Ω coplanar stripline is employed to connect the MSM photodiodes. The phase velocity of coplanar stripline (about 35% faster than the velocity of optical wave) is slowed down by the periodic capacitance loading of the MSM photodiodes.

Fig. 1(b) shows the epitaxial layer structure of the device. It consists of a 3-μm-thick $Al_{0.25}Ga_{0.75}As$ lower cladding layer, a 0.5-μm-thick $Al_{0.15}Ga_{0.85}As$ waveguide core layer, a 0.2-μm-thick $Al_{0.35}Ga_{0.65}As$ upper cladding layer, and a 0.2-μm-thick low-temperature (LT) grown GaAs absorbing layer. The absorbing layer is designed to be on the top surface and evanescently coupled to the passive waveguide to facilitate device contact and fabrication. The material composition and thickness of each epitaxial layers are designed such that only the fundamental mode exists in both the passive optical waveguide and the active photodiode regions. In order to achieve high-saturation power, the confinement factor of the MSM absorbing layer is designed to be very low (= 1.5%).

The VMDP is first theoretically simulated using the transmission matrix approach [13], taking into consideration the effect of transit time, parasitic RC, and the residue velocity

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L. Y. Lin, M. C. Wu, and T. Itoh are with the University of California-Los Angeles, Electrical Engineering Department, 405 Hilgard Avenue, Los Angeles, CA 90095-1594 USA.

T. A. Vang and R. E. Muller are with the Jet Propulsion Laboratory, Pasadena, CA 91109-8099 USA.

D. L. Sivco and A. Y. Cho are with Lucent Technologies, Bell Labs Innovations, Murray Hill, NJ 07974 USA.

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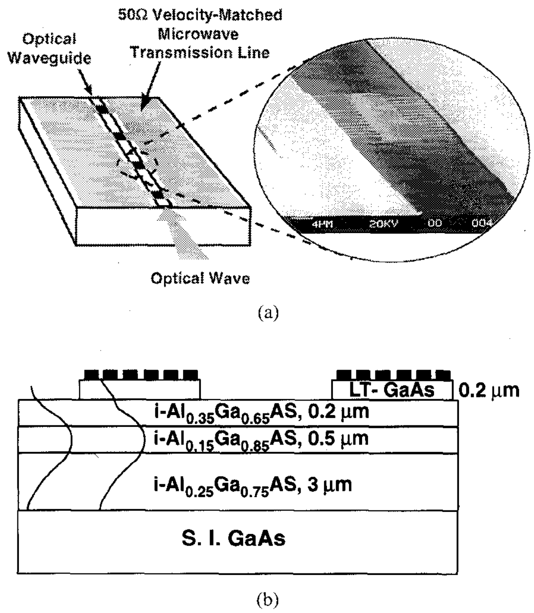

Fig. 1. (a) The schematic structure of the velocity-matched distributed photodetectors (VMDP) and the SEM micrograph of the MSM photodiode. (b) The epitaxial layer structure of the VMDP.

mismatch. The details of the theoretical simulation and the design trade-offs between saturation power and bandwidth will be reported elsewhere. The simulated frequency responses of the VMDP versus the number of photodiodes are shown in Fig. 2. The bandwidth of the VMDP with one MSM detector is basically the same as that of the conventional high-speed MSM photodetector [3], and can be as high as several hundred GHz, though the quantum efficiency is low because of the high-power design. The quantum efficiency increases with increasing number of photodiodes, without decreasing the bandwidth. The maximum quantum efficiency of 40% is limited by the 50-Ω matched input termination assumption (50% of photocurrent is absorbed by the terminated input end) and the coupling loss between the active and passive waveguide regions (theoretical coupling efficiency = 98%).

The fabrication process of the VMDP is described in the following: first, the MSM patterns with 0.3-μm finger width and 0.2-μm spacing were defined on the spin-coated polymethymethacrylate (PMMA) using electron-beam lithography. The exposed PMMA was developed in 2-ethoxyethanol:methanol (3:7). Then the Ti/Pt/Au (100 Å/100 Å/300 Å) electrodes were deposited by e-beam evaporation and lift-off technique. Active mesas of photodiodes are defined by etching the GaAs absorption layer down to the $Al_{0.35}Ga_{0.65}As$ layer. A 3 μm-wide ridge waveguide is formed by wet chemical etching. Finally, Ti–Pt–Au (250 Å/500 Å/3000 Å) was evaporated and lifted off to form the coplanar stripline. The scanning electron micrograph (SEM) of the MSM photodiode is shown in the inset of Fig. 1(a).

III. Experiment and Results

The impulse response of the VMDP is characterized by a femtosecond Ti:Sapphire laser. The laser was modelocked at 860 nm with a pulse width of 120 fs and a repetition rate of 80 MHz. The device under test was biased at −4 V through a bias-Tee. The generated microwave signal was collected at the output end of the transmission line by a 50-GHz high-frequency probe (Picoprobe from GGB Industries). The signal is then sent to an HP digitizing oscilloscope with 50 GHz bandwidth through a microwave cable. Part of the signal is split by a microwave power splitter and amplified to trigger the digitizing oscilloscope. The timing jitters of the measured signal are greatly reduced in this configuration.

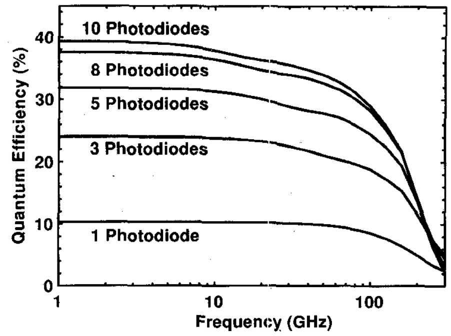

Fig. 2. The simulation results for the quantum efficiency versus the frequency of the VMDP with different number of active photodiodes. The length of each photodiode is 15 μm.

The electrical frequency response is obtained from the Fourier transform of the impulse response. The device under test consists of three active MSM photodiodes. Each photodiode is 15-μm-long and the spacing between the photodiodes is 150 μm. The input end of the transmission line is not terminated for the current measurement. The impedance of the periodically loaded transmission line is characterized to be close to 50 Ω (within 6% deviation) from 0.13 GHz to 50 GHz using HP8510C network analyzer. The impulse response of the device with the microwave connection is shown in the inset of Fig. 3. The ringing in the trailing edge results from the reflection from the microwave amplifier for the triggering signal. The frequency response of the microwave cable, splitter, bias-T, and probe is separately characterized to 50 GHz by HP8510C network analyzer. The overall and calibrated frequency response is shown in Fig. 3. The 3-dB bandwidth of 49 GHz appears to be limited by the bandwidth of the digitizing oscilloscope.

To investigate the ac saturation effect, the impulse response of the VMDP is measured with increasing optical powers. Fig. 4 shows the normalized ac quantum efficiency and the peak photocurrent versus the input optical pulse energy. At low optical power, the ac quantum efficiency is equal to the dc quantum efficiency (12.3% for VMDP with three photodiodes). As the input optical intensity increases, the number of the optically generated carriers increases. This results in the electric field screening effect and the peak intensity of the RF signal starts to saturate. The bandwidth remains unchanged as the peak photocurrent increases to 19 mA ($\eta_{AC}/\eta_{DC} \sim 0$ dB), and reduces to 42 GHz when η_{AC}/η_{DC} decreases to −1 dB. At 1-dB compression, the measured peak photocurrents are 28, 56, and 66.5 mA for the VMDP's with 1, 3, and 5 photodiodes, respectively. The bandwidth of the VMDP with 3 photodiodes is the same as that of the VMDP with

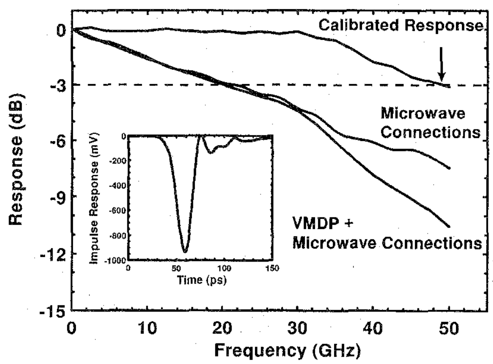

Fig. 3. The electrical frequency response of the VMDP obtained from the Fourier transform of the impulse response (inset of the figure). The effect of the microwave connection is separately calibrated by a network analyzer and deconvloved from the overall response.

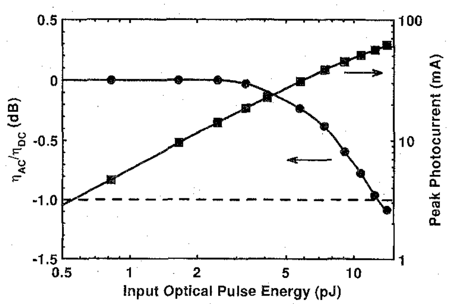

Fig. 4. The normalized ac quantum efficiency and the peak photocurrent versus the input optical pulse energy for VMDP with three active photodiodes.

1 photodiode, and degrades slightly when the number of the photodiodes increases to 5. Theoretical simulation of the peak saturation photocurrent versus the number of photodiodes was performed for various coupling efficiencies κ between the passive and active waveguide regions. The measured data agrees very well with the curve of $\kappa = 88\%$. This coupling efficiency is somewhat lower than the theoretical value of 98%. The discrepancy is attributed to the slight overetch during removal of the absorbing layer. By employing selective etching, better coupling efficiency is expected. The peak saturation photocurrent can be further increased to >100 mA by improving the coupling efficiency from 88% to 95% and increasing the number of photodiodes to ten. The quantum efficiency of the device can be improved by optimizing the coupling efficiency of the lensed fiber (currently $\sim$45%) and applying anti-reflection (AR)-coating to the VMDP facet (30% Fresnel loss), in addition to improving the coupling efficiency between the passive and active waveguide regions.

IV. Conclusion

We have demonstrated a velocity-matched distributed photodetector (VMDP) with nanoscale MSM photodiodes. Through the velocity matching between the optical waveguide and the microwave transmission line, VMDP can achieve large effective absorption volume and high-saturation power without sacrificing its bandwidth. A very high-saturation photocurrent of 56 mA and an instrument-limited 3-dB bandwidth of 49 GHz have been achieved. Further improvement in saturation power and quantum efficiency is expected with more precise control of fabrication processes. The high-power, high-frequency VMDP can greatly improve the RF insertion loss, dynamic range, and noise performance of analog fiber-optic links.

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