High-Speed Photodetectors with High Saturation for High Performance Microwave Photonic Systems

L.Y. Lin, M. C. Wu, and T. Itoh
UCLA, Electrical Engineering Department
405 Hilgard Avenue, Los Angeles, CA 90095-1594, USA
Tel: (310)206-4820 Fax: (310)206-4819 EMail: itoh@ee.ucla.edu
T. A. Vang and R. E. Muller
Jet Propulsion Laboratory, Pasadena, CA 91109-8099
D. L. Sivco and A. Y. Cho
AT&T Bell Laboratories, Murray Hill, NJ 07974

Abstract: We proposed a velocity-matched distributed photodetector (VMDP) to achieve high saturation power and large bandwidth. The VMDP with 56 mA saturation photocurrent and an instrument-limited 3-dB bandwidth of 49 GHz is demonstrated.

I. INTRODUCTION

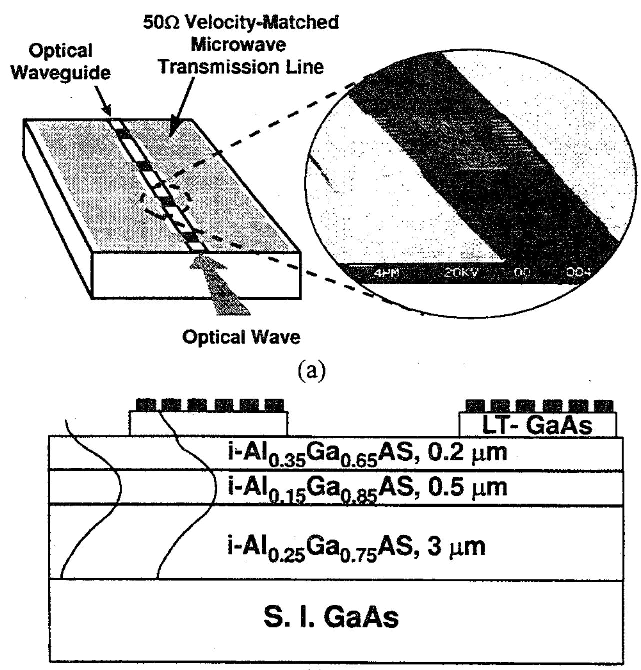
High power, high speed photodetectors are crucial in microwave fiber optic links to provide high gain, large spurious free dynamic range, and high signal-to-noise ratio [1]. They are also important for optical heterodyned receivers and optoelectronic generation of high power microwaves and millimeter-waves. Conventional high speed photodetectors [2-6] cannot achieve high saturation power because of the small absorption volume (on the order of 1 μm^3) required to achieve high speed operation. 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].

We 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 active photodiodes serially connected by a passive optical waveguide, and the photocurrents are collected *in phase* by a separate output microwave transmission line. By optimizing the geometries of the photodiodes, waveguide, and transmission line independently, velocity-matching between the optical wave and the microwave can be achieved [11]. One unique advantage of the VMDP is that the velocity-matched 50Ω 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 paper, the performance of the high power, high frequency VMDP with nanoscale MSM photodiodes will be demonstrated. A peak saturation photocurrent of 56 mA (at 1-dB compression of quantum efficiency) and an instrument-limited 3dB bandwidth of 49 GHz are achieved.

II. DESIGN 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 50Ω 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 to achieve velocity-matching.

Figure 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%) so that only a small portion of the light is coupled into each active photodiode.



(b)

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.

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. EXPERIMENTS

The experimental setup for measuring the RF response and saturation is shown in Fig. 2. A femtosecond Ti:Sapphire laser is used as the light source for characterizing the impulse response of the device. 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 -4V 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.

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 frequency response of the microwave cable, splitter, bias-T, and probe is separately characterized by the

HP8510C network analyzer. The 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.

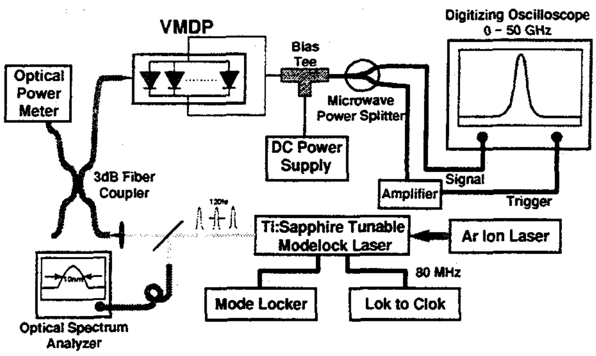


Fig. 2 The experimental setup for measuring RF response and saturation

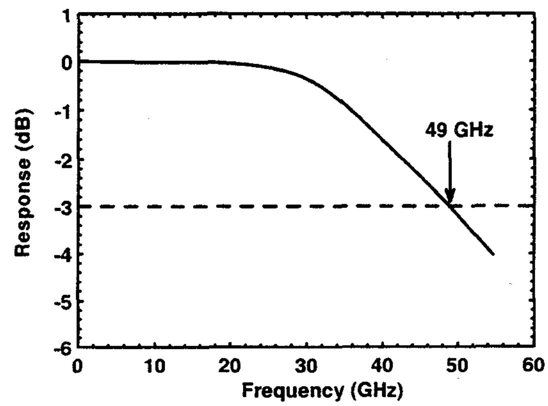


Fig. 3 The electrical frequency response of the VMDP obtained from the Fourier transform of the impulse response.

To investigate the AC saturation effect, the impulse response of the VMDP is measured with increasing optical powers. Figure 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 (η_{AC}/η_{DC} ~ 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 VMDPs with 1, 3, and 5 photodiodes, respectively. The bandwidth of the VMDP with 3 photodiodes is the same as that of the VMDP with 1 photodiode, and it starts to degrade slightly when the number of the photodiodes increases to 5. Figure 5 shows the calculated peak saturation photocurrent versus the number of photodiodes for three different coupling efficiencies between the passive and active waveguide regions, κ = 88%, 95%, and 98%, respectively. The measured data agrees very well with the curve of κ = 88%. This coupling efficiency is slightly lower than the theoretical value of 98%. The discrepancy is attributed to the slight overetch during the fabrication process. 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 further improved by optimizing the coupling efficiency of the lensed fiber (currently ~ 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.

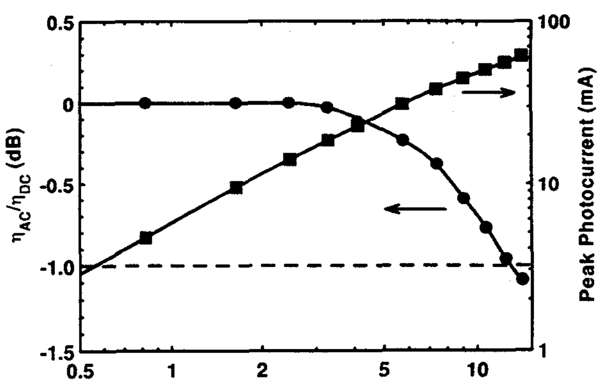


Fig. 4 The normalized AC quantum efficiency and the peak photocurrent versus the input optical pulse energy for VMDP with three active photodiodes.

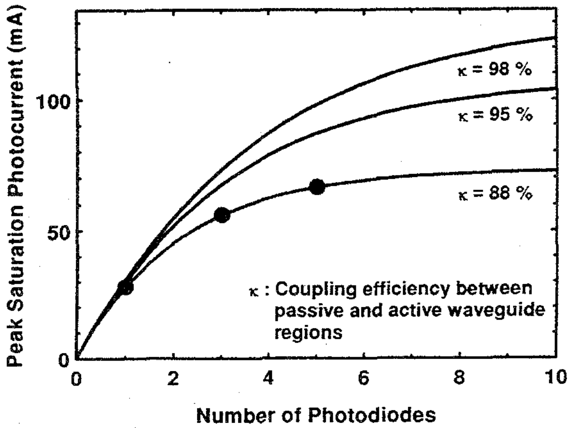


Fig. 5 The theoretical and experimental peak saturation photocurrents of VMDP versus the number of photodiodes for three coupling efficiency between passive waveguide and active photodiode regions: $\kappa = 88\%$, 95%, and 98%.

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 3dB bandwidth of 49 GHz have been achieved. The high power, high speed VMDP can significantly improve the link gain, dynamic range, and noise performance of analog fiber-optic links. The results show that VMDP is ideal for high performance microwave photonic systems.

Acknowledgment: The authors would like to thank Professor K. L. Wang for loaning the HP digitizing oscilloscope, and Drs. S. Forouhar, N. Mysoor of JPL, and J. Harvey of ARO for helpful discussions. This work is supported by ARPA, U.S. Army Research Office under grant #DAAH04-95-I-0405, JSEP, and NASA OSAT funded through JPL.

References:

[1] C. H. Cox, "Analog fiber-optic links with intrinsic gain," *Microwave Journal*, Vol. 35, no. 9, pp. 92-99, 1992.

[2] K. D. Li, A. S. Hou, E. Ozbay, B. A. Auld, and D. M. Bloom, "2-picosecond, GaAs photodiode optoelectronic circuit for optical correlations," *Appl. Phys. Lett.*, Vol. 61, no. 26, pp. 3104-3106, 1992.

[3] S. Y. Chou and M. Y. Liu, "Nanoscale tera-hertz metal-semiconductor-metal photodetectors," *IEEE J. Quantum Elec.*, Vol. 28, no. 10, pp. 2358-2368, 1992.

[4] K. Kato, A. Kozen, Y. Muramoto, Y. Itaya, T. Nagatsuma, and M. Yaita, "110-GHz, 50%-efficiency mushroom-mesa waveguide p-i-n photodiode for a 1.55-μm wavelength," *IEEE Photonics Tech. Lett.*, Vol. 6, no. 6, pp. 719-721, 1994.

[5] K. S. Giboney, R. L. Nagarajan, T. E. Reynolds, S. T. Allen, R. P. Mirin, M. J. W. Rodwell, and J. E. Bowers, "Travelling-wave photodetectors with 172-GHz bandwidth and 76-GHz bandwidth-efficiency product," *IEEE Photonics Tech. Lett.*, Vol. 7, no. 4, pp. 412-414, 1995.

[6] Y. G. Wey, K. Giboney, J. Bowers, M. Rodwell, P. Silvestre, P. Thiagarajan, and G. Robinson, "110-GHz GaInAs/InP double heterostructure p-i-n photodetectors," *IEEE J. Lightwave Tech.,* Vol. 13, no. 7, pp. 1490-1499, 1995.

[7] K. J. Williams, R. D. Esman, and M. Dagenais, "Nonlinearities in p-i-n microwave photodetectors," *IEEE J. Lightwave Tech.*, Vol. 14, no. 1, pp. 84-96, 1996.

[8] A. R. Williams, A. L. Kellner, X. S. Jiang, and P. K. L. Yu, "InGaAs/InP waveguide photodetector with high saturation intensity," *Elec. Lett.*, Vol. 28, no. 24, pp. 2258-2259, 1992.

[9] H. F. Taylor, O. Eknoyan, C. S. park, K. N. Choi, and K. Chang, "Traveling wave photodetectors," *Proc. SPIE*, Vol. 1217, *Optoelectronic Signal Processing for Phased-Array Antennas II*, pp. 59-63, 1990.

[10] V. M. Hietala, G. A. Vawter, T. M. Brennan, and B. E. Hammons, "Traveling-wave photodetectors for high-power, large-bandwidth applications," *IEEE Trans. On Microwave Theory and Tech.*, Vol. 43, no. 9, pp. 2291-2298, 1995.

[11] M. C. Wu and T. Itoh, "Ultrafast Photonic-To-Microwave Transformer (PMT)," IEEE LEOS Summer Topical Meeting on Optical Microwave Interactions, Santa Barbara, CA, July 19-21, 1993.

[12] L. Y. Lin and M. C. Wu, "Ultrafast high power photodetectors," IEEE LEOS Summer Topical Meetings, Keystone, CO, August 7-11, 1995.