A Novel Monolithic Distributed Traveling-Wave Photodetector with Parallel Optical Feed

Sanjeev Murthy, *Student Member, IEEE*, Thomas Jung, Tai Chau, Ming C. Wu, *Member, IEEE*, Deborah L. Sivco, and Alfred Y. Cho, *Fellow, IEEE*

***Abstract*—We report on a novel monolithic distributed traveling wave photodetector with parallel optical feed to an array of individual photodiodes using an integrated multimode interference (MMI) coupler to attain high saturation current. The parallel optical feed reduces the maximum photocurrent and photocurrent density seen by any single photodiode, thus increasing the maximum linear photocurrent of the detector. We have successfully fabricated a device with a maximum linear photocurrent of 20 mA and a responsivity of 0.13 A/W.**

***Index Terms*—High-power devices, integrated optics, multimode interference, MSM photodiodes, photodetectors, traveling wave.**

I. Introduction

HIGH-POWER high-speed photodetectors are essential in high performance radio-frequency (RF) photonic links to reduce RF insertion loss, increase spurious free dynamic range and to increase signal-to-noise ratio [1]. One of the major factors limiting the performance of current RF photonic links is the maximum linear photocurrent of the photodetector [2]. Conventional high-speed detectors have a small absorption volume and consequently cannot achieve high saturation power and high bandwidth simultaneously. Several approaches have been proposed to increase the saturation power of photodetectors [3]–[7]. Previously, velocity matched distributed photodetectors (VMDP) have demonstrated high bandwidth and high saturation current [3], [4]. Due to the exponential decay of photons in the waveguide, the first photodiode has highest photocurrent density. As a result, the maximum linear photocurrents of the VMDP's are usually limited by either catastrophic failure [8] or saturation of the first photodiode. Higher linear photocurrent has been obtained in waveguide photodetectors through uniform distribution of the total photocurrent [6] or by increasing carrier transit times [7].

In this letter, we propose to reduce the peak photocurrent density of VMDP by evenly distributing the input light to N photodiodes with a multimode interference (MMI) coupler (Fig. 1). The outputs of these N photodiodes are still collected in phase by a separate microwave transmission line to maintain the high bandwidth. Velocity matching of discrete photodiodes with parallel optical feed has previously been demonstrated using a quasi-transmission line [9] and through multibeam excitation [10]. We present here, a monolithic device consisting of distributed detectors with an integrated MMI coupler fabricated on an InP substrate. The parallel fed traveling wave photodetector thus has uniform distribution of photocurrents in the individual photodiodes, and can potentially achieve an N-fold increase in maximum linear photocurrent.

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S. Murthy, T. Jung, T. Chau, and M. C. Wu are with the Electrical Engineering Department, University of California Los Angeles, Los Angeles, CA 90095 USA (e-mail: sanjeev@icsl.ucla.edu).

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

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II. Design & Fabrication

In the schematic of the parallel fed MMI-VMDP shown in Fig. 1, the individual detectors in the device were chosen to be metal–semiconductor–metal (MSM) photodiodes operating at a wavelength of $1.55\,\mu$m. The device was fabricated on a wafer based on the InGaAs–InAlAs–InP materials grown by molecular beam epitaxy (MBE). The epitaxial layers consist of a 0.5-μm-thick $In_{0.52}Al_{0.18}Ga_{0.3}As$ core layer, bound by $0.2\,\mu$m of $In_{0.52}Al_{0.37}Ga_{0.11}As$ lower cladding and an upper cladding consisting of $0.2\,\mu$m of $In_{0.52}Al_{0.37}Ga_{0.11}As$ and $0.2\,\mu$m of $In_{0.52}Al_{0.48}As$ for the passive optical waveguide. The absorbing region for the detectors is a 0.15-μm-thick $In_{0.53}Ga_{0.47}As$ layer above the upper cladding. The absorbing region is capped by a 660-Å-thick graded superlattice, Schottky barrier enhancement layer. The confinement factor in the absorbing layer of the detector region is 1% and the coupling coefficient between the passive waveguide and the photodiode region is 98.6% for two-dimensional slab waveguide modes. The length of the individual MSM diodes is $80\,\mu$m.

We chose an MMI power splitter [11] to implement the parallel optical feed because of its ease of fabrication, low losses and higher fabrication tolerances compared to a Mach–Zender or Y-branch based splitters. The input and output waveguides of the MMI section are $6\,\mu$m wide. The output waveguides of the splitter are separated by $4\,\mu$m to reduce crosstalk. Detectors with 1×4 and 1×8 splitters were fabricated. The MMI sections were designed using beam propagation methods. The MMI section of the 1×4 splitter is $40\,\mu$m wide and 0.905 mm long while the 1×8 splitter is $80\,\mu$m wide and 1.805 mm long. A coplanar strip (CPS) microwave transmission line with $50\,\Omega$ impedance is used to collect the photocurrents in phase. The microwave velocity has been matched to the optical velocity to increase the bandwidth, though in our initial demonstration, the bandwidth of the device is limited by the transit time of the MSM diodes.

The fabrication process began with the detector region being defined by wet etching. The passive waveguides to feed the detectors and the MMI waveguide were then wet-etched by removing the upper cladding. The passive waveguides are thus

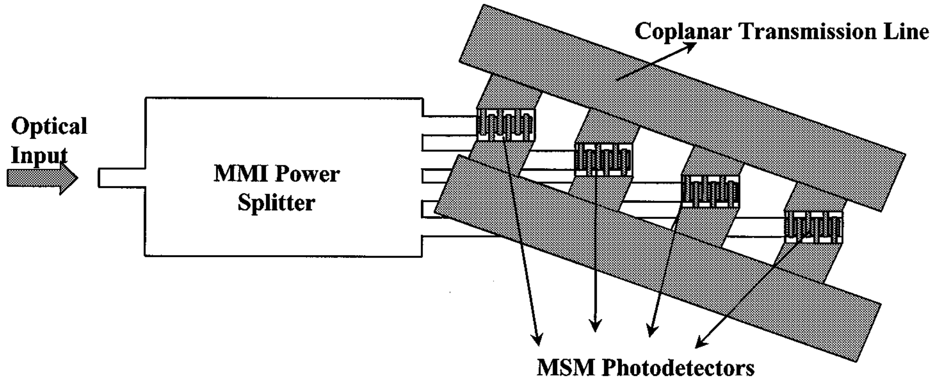
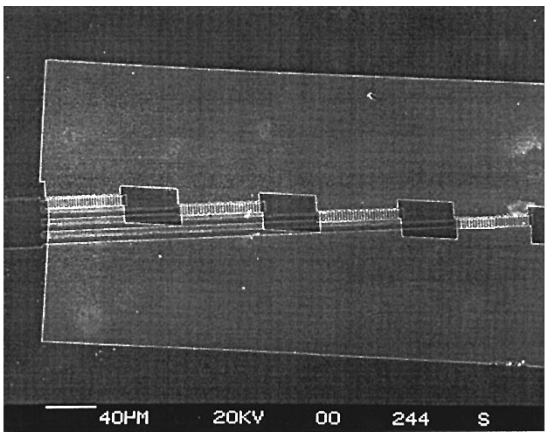
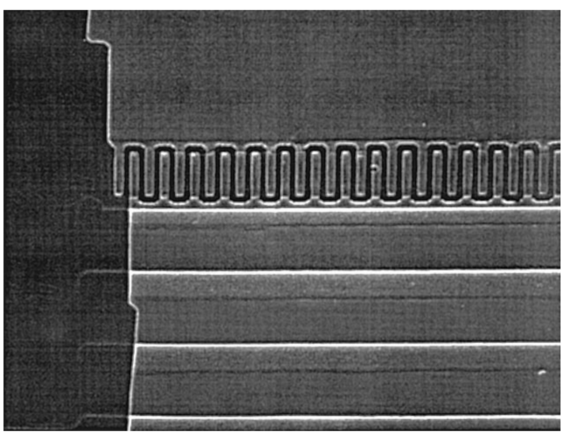


Fig. 1. Schematic of the parallel feed integrated MMI-VMDP.



(a)



(b)

Fig. 2. (a) SEM photograph of the fabricated devices and (b) metal fingers of the MSM diodes.

0.4 μm deep. A 2000-Å-thick silicon nitride passivation layer was used to increase the breakdown voltage. The Schottky metal contacts for the MSM detectors were fabricated by evaporating 200 Å/300 Å/2000 Å of Ti–Pt–Au. The finger width is 1 μm and the finger spacing is 1 μm. Fig. 2 shows the scanning electron micrographs (SEM) of the fabricated devices.

III. Measurements and Discussion

High-power DC-photocurrent measurements are shown in Fig. 3. The device with the highest linear photocurrent is shown for each type of detector. The response of the detector with the 1×4 splitter saturates at a current of 13.6 mA (for a 1 dB decrease from the linear photocurrent value). The detector with the 1×8 splitter, however, remains linear until it fails at a current of 20.1 mA. The benefits of parallel distribution of light to the detectors can be seen from the fact that the detector with the 1×4 splitter saturates at a lower current value compared to the detector with the 1×8 splitter. The maximum linear photocurrent can be further increased with optimization of the design.

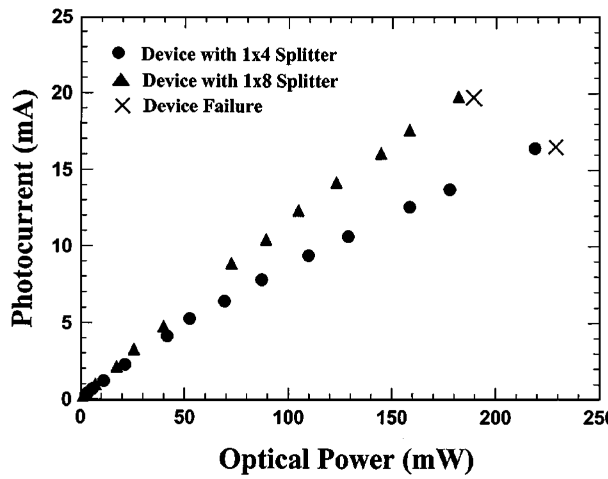


Fig. 3. Photocurrent measurements showing maximum linear photocurrent of the detectors.

Other device parameters are similar for both types of detectors and the measurement results are summarized below. The photoresponse of the devices was measured using a Photonetics tunable external cavity semiconductor laser and a HP4145B Semiconductor Parameter Analyzer. The devices typically show a responsivity ranging from 0.1–0.13 A/W. The best responsivity obtained was 0.15 A/W. The device bandwidth for a detector with a 1×4 MMI splitter, measured using an HP8510C network analyzer, a 40-GHz GGB Industries picoprobe and an HP83420A Lightwave test set, was found to be 7.2 GHz (Fig. 4) at a bias voltage of 5V and a dc current of 2 mA. The device bandwidth was similar for detectors with 1×8 splitters. We did not observe any significant variation in bandwidth with variation in detector current from 0.5 to 2 mA. The photocurrent was limited to 2 mA in these measurements

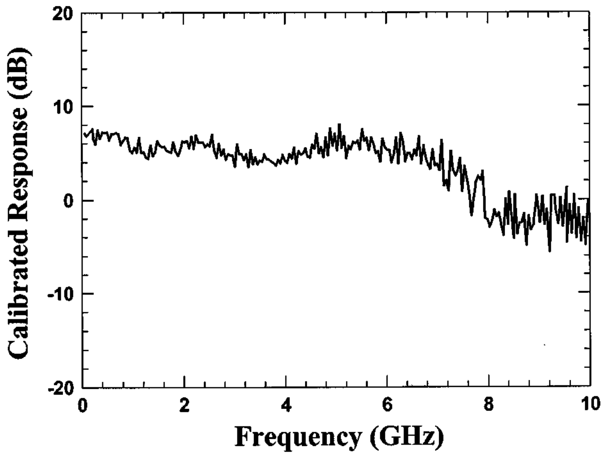


Fig. 4. Bandwidth measurement of the MMI-VMDP at a bias voltage of 5 V and a dc current of 2 mA.

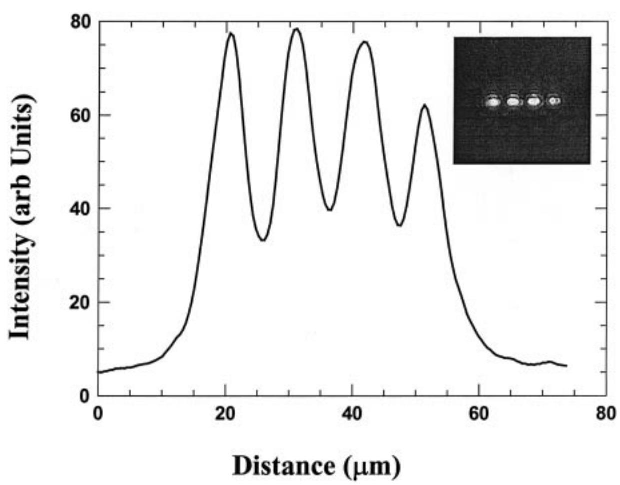


Fig. 5. Intensity profile of the output of the 1 × 4 MMI splitter. IR picture of the facet is shown in the inset.

to avoid damaging the devices. The dark current of the devices varied from less than 50 nA to $4\,\mu$A at 5 V dc bias. The breakdown voltage of the devices was typically around 7 V. The responsivity of the detectors varied less than 6% in the wavelength range 1530–1570 nm. The devices show maximum photocurrent for TE polarization and the photocurrent reduces by 3.5 dB for TM polarization.

To investigate the excess loss of the MMI splitter, the output at the cleaved facet of the MMI power splitter was photographed using a Hamamatsu C2741 IR camera. The IR picture of the facet (inset) and the intensity profile of the spots are shown in Fig. 5. The large variation in the intensity of one of the output spots shown in Fig. 5 is due to that output waveguide having a residual portion of the absorbing region of the detector while cleaving the splitter from the detectors. The output shows a variation of less than 1.25 dB across the four output waveguides (including the waveguide with absorbing region). The excess loss of the 1×4 MMI splitter shown in Fig. 5 was measured to be 1.5 dB.

The low responsivity is due to variation in the MMI dimensions due to nonuniformity in the wet etch process. The responsivity can be improved by using a dry-etch process for MMI splitter definition. The bandwidth is limited by the $1\,\mu$m MSM finger spacing and absorption in the low-field regions of the MSM structure. The bandwidth can be increased either through e-beam lithography or through vertical transport p-i-n/Schottky diodes.

IV. Conclusion

We have proposed and successfully demonstrated a novel parallel-fed distributed photodetector with an integrated MMI power splitter to increase the power handling capability of traveling wave photodetectors. A maximum linear photocurrent of 20 mA was achieved along with a responsivity of 0.13 A/W in a detector with an integrated 1×8 MMI splitter.

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