Distributed Balanced Photodetectors for High-Performance RF Photonic Links

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***Abstract*—A novel velocity-matched distributed balanced photodetector with a 50-Ω coplanar waveguide output transmission line has been experimentally demonstrated in the InP–InGaAs material system. Distributed absorption and velocity matching are employed to achieve high-saturation photocurrent. A common mode rejection ratio of 27 dB has been achieved. The RF link experiment conducted at 6.48 GHz shows that the laser intensity noise has been suppressed by more than 17 dB.**

***Index Terms*— Analog fiber-optic links, balanced photodetectors, noise suppression, optical receivers, RF photonics.**

I. Introduction

BALANCED PHOTODETECTORS are of great interest to analog fiber-optic links because they can suppress laser relative intensity noise (RIN) and amplified spontaneous emission noise (ASE) from erbium-doped fiber amplifiers (EDFA's) [1]. Because balanced photodetectors can achieve shot noise-limited link performance, we can continue to improve the noise figure and the spurious-free dynamic range (SFDR) of externally modulated links by increasing the power of the optical carrier. Therefore, balanced photodetectors with broad bandwidth and high-saturation photocurrents are particularly important for analog fiber-optic link applications. Though discrete balanced photodetectors with high-saturation power have been reported, their bandwidth is limited [2]. Most of the reported integrated balanced receivers suffer from low saturation power and are not suitable for analog links [3]–[5]. Previously, we have reported a velocity-matched distributed photodetector (VMDP) with a peak saturation photocurrent of 56 mA and a 3-dB bandwidth of 49 GHz [6]. Recently, InP-based long wavelength VMDP has also been reported [7]. Compared with other photodetector structures, the VMDP is more suitable for implementing the balanced photodetection since it has separate optical and microwave waveguides. In this letter, we propose and demonstrate a novel, monolithic distributed balanced photodetector that can simultaneously achieve high-saturation photocurrent and large bandwidth. A common mode rejection ratio of 27 dB and a noise suppression of 17 dB have been experimentally demonstrated.

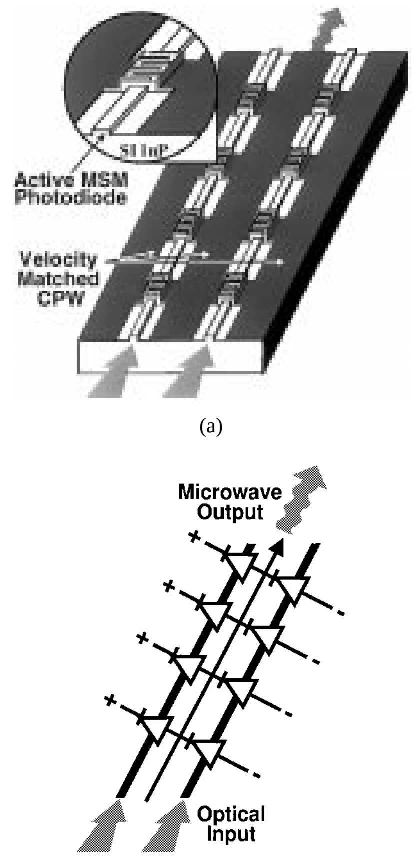

Fig. 1. (a) Schematic structure of the distributed balanced photodetector. Inset shows the active region with an MSM photodiode. (b) Photodiodes connected to the optical waveguide in balanced detection mode.

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II. Design and Fabrication

Fig. 1 shows the schematic of the distributed balanced photodetector. It consists of two input optical waveguides, two arrays of high-speed metal–semiconductor–metal (MSM) photodiodes distributed along the optical waveguides, and a 50-Ω coplanar waveguide (CPW) output transmission line. The diodes are 23 μm long and 5 μm wide. The MSM fingers with 1 μm width and 1-μm spacing are patterned by optical lithography. The central conductor of the CPW has a width of 55

μm and the separation between the central conductor and the ground conductors is 85 μm. The 10.5-μm overlap of the MSM fingers is designed to provide the required capacitive loading for velocity matching. Unlike previously reported slow-wave CPW [8] that ignored the resistance of the MSM photodiode fingers, finite metal thickness, and transmission line discontinuities in their quasistatic calculations, we used a full-wave analysis to achieve the velocity and impedance matching.

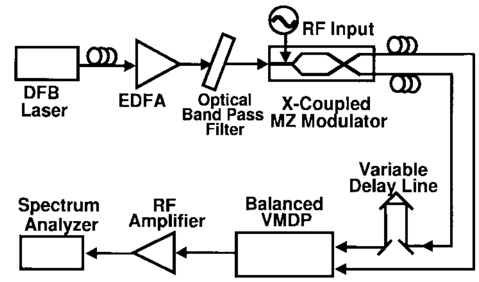
The distributed balanced photodetector inherits the basic advantages of the VMDP, namely, high-saturation photocurrent, high quantum efficiency, and large bandwidth. It should be noted that even though only the difference current (ac signal) is collected in the balanced photodetector, the dc light is still absorbed in the photodiodes. As a result, high-dc saturation photocurrent is required for the distributed balanced photodetectors. By coupling only a small fraction of light from the passive waveguide to each individual photodiode, the photodiodes are kept below saturation even under intense optical input. The bandwidth of the distributed balanced photodetector remains high because of the velocity matching.

Beam propagation method (BPM) simulation was used to investigate the optical properties of the balanced VMDP. The simulation shows that an input beam with TM polarization contributes to the optimum performance. Details of the simulation of the polarization dependence of absorption and optical coupling loss between photodiodes will be discussed elsewhere. The optical waveguide consists of the following: a 200-nm-thick $In_{0.52}Al_{0.37}Ga_{0.11}As$ lower cladding layer, a 500-nm-thick $In_{0.52}Al_{0.178}Ga_{0.302}As$ core region, a 200-nm-thick $In_{0.52}Al_{0.37}Ga_{0.11}As$ first upper cladding layer, and a thin $In_{0.52}Al_{0.48}As$ second upper cladding layer. The 150-nm-thick absorption region is located on top of the waveguide for evanescent coupling. Since the Schottky barrier height of most metals on the InGaAs is typically between 0.2–0.3 eV, an $In_{0.52}Al_{0.48}As$ cap layer is used to increase the Schottky barrier height and therefore decrease the dark current in the photodiodes [9]. A graded layer is incorporated in the structure to reduce the minority carrier trapping at the InAlAs–InGaAs band-edge discontinuity.

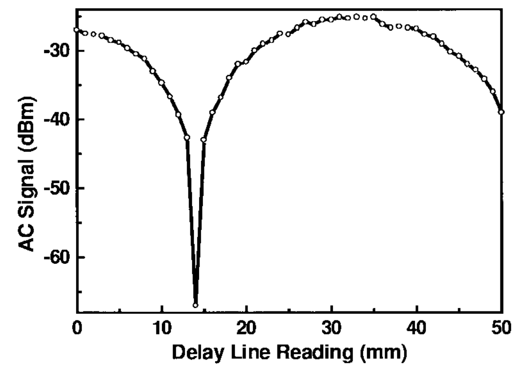
Fabrication of the receiver started with removing the InGaAs layer except in the active areas of the photodiodes. Ridge waveguides with 100-nm ridge height were formed by wet chemical etching. The active regions of the photodiodes were defined by opening $6 \times 23\,\mu$m windows on the 150-nm-thick silicon nitride (Si_3N_4) film deposited by plasma-enhanced chemical vapor deposition (PECVD). Buffered HF was used to remove the Si_3N_4 in the windows. The Ti–Au electrodes and contact pads of the MSM photodiodes were then delineated by standard liftoff processes. The tips of the MSM fingers are placed on top of Si_3N_4 to suppress the soft breakdown and enable the MSM diodes to operate over a wider range of bias voltage [10]. Finally, a 350-nm-thick coplanar waveguide was formed by standard lift-off process to connect the distributed balanced photodetectors.

III. Measurements and Discussions

The balanced VMDP exhibits very good electrical and optical characteristics. The dark current is measured to be 28 μA/cm^2 at 10-V bias, the lowest reported for InAlAs–InGaAs MSM photodiodes. By coupling light directly from a lensed fiber, the average dc responsivity (15 devices tested) was measured to be 0.45 A/W at 8-V bias. Responsivity as high as 0.6 A/W has been observed in some devices. The photo response of a laser beam with TM polarization is measured to be ~1.7 dB higher than that of TE polarization. The coupling efficiency of the lensed fibers in our setup was calculated to be ~50%. With antireflection (AR) coating to the balanced receiver facet (30% Fresnel loss), the average responsivity can be increased to 0.64 A/W.



(a)

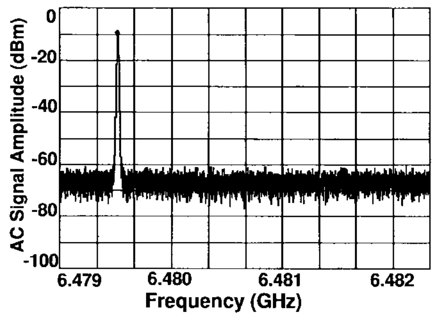


(b)

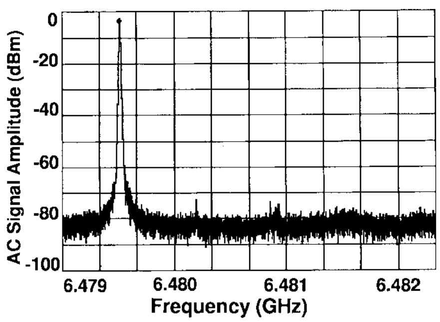
Fig. 2. (a) Balanced detection setup. The complimentary input signals are produced by the X-coupled MZ modulator. (b) Peak power of ac signal in balanced mode versus the delay. For RF signal at 8 GHz, the period was measured to be 38.75 mm, which is very close to the theoretical value. The power difference between 0° and 180° phase difference is more than 44 dB.

An HP 8510C network analyzer was used to measure the characteristic impedance and the microwave return loss (S_{11}) of the balanced receiver. The characteristic impedance of the receiver is very well matched to 50 Ω. The S_{11} is as low as -30 dB from 45 MHz to 40 GHz. The CPW has very low insertion loss. The measured S_{12} shows a drop of only 0.6 dB from 45 MHz to 40 GHz.

The frequency response of the balanced VMDP was first characterized with light coupled to one waveguide only. Using the optical heterodyne technique with two external cavity tunable semiconductor lasers at 1.55 μm, the 3-dB bandwidth was found to be 16 GHz for both photodetector arrays. The bandwidth is currently limited by the carrier transit time of the MSM photodiodes. Since our bandwidth of the capacitance loaded CPW is much greater than 40 GHz, the bandwidth of the balanced VMDP can be increased by scaling down the MSM photodiodes. Theoretical simulation indicates that bandwidth >100 GHz is achievable.



(a)



(b)

Fig. 3. The ac signal in unbalanced and balanced detection modes are plotted. The balanced output is almost 6 dB higher in amplitude than the unbalanced signal. Noise suppression of greater than 17 dB is achieved.

Fig. 2(a) depicts the experimental setup for balanced detection. A distributed feedback (DFB) laser with 1542-nm wavelength and 0-dBm output power is employed as the optical source. It is amplified by an EDFA and then filtered by an optical bandpass filter with 2-nm bandwidth. The microwave signal was modulated onto the optical carrier by an X-coupled Mach–Zehnder modulator (MZM), which produces two complementary outputs for the balanced VMDP. The outputs are coupled to the balanced VMDP by two lensed fibers. To maximize the signal enhancement and noise cancellation, it is important to match the amplitudes and phases of the two detected microwave signals. In our experiment, a variable attenuator was used to match the amplitudes of the photocurrents. Typical balance between the VMDP was within 2% of the total photocurrent reading, which was limited to 4 mA in our current experiments. Since the accuracy of cutting optical fiber lengths is about 1 mm, a variable delay line was used to ensure equal optical path lengths between the two fibers, which is necessary to produce the broad-band 180° out-of-phase RF signals for balanced VMDP. The output from the balanced VMDP was measured using a spectrum analyzer. A common mode rejection ratio of -27 dB has been achieved.

Balanced detection is achieved by applying a bias of 8 V between the two ground electrodes of the CPW. A custom-made high-frequency probe with an integrated dc-blocking capacitor on one ground probe is used to collect the microwave output signal. The dc difference photocurrent is monitored through the bias-T connected to the probe. To verify the balanced detection, we modulated the optical input at 8 GHz and varied the delay of the fiber-optic delay line from 0 to 50 mm. Fig. 2(b) shows the RF signal versus the delay. When the RF signals have 0° phase difference, the ac output is cancelled in balanced mode. At 180° phase difference, the RF signal is amplified, the extinction ratio is more than 44 dB.

Fig. 3 shows the RF spectrum of the output from the balanced VMDP in the unbalanced (only one waveguide is illuminated) and the balanced mode. Suppression of the noise floor by 17 dB has been observed in the balanced mode over a wide frequency range from 6 to 15 GHz. The signal is also enhanced by 6 dB.

IV. Conclusion

We have successfully designed, fabricated, and experimentally demonstrated a balanced velocity-matched distributed photodetector (VMDP) with both impedance and velocity matching. The device exhibits a very low dark current and a high external quantum efficiency of 0.60 A/W. Using the balanced VMDP, the RIN and EDFA-added noise have been suppressed by 17 dB, and the RF signal has been enhanced by 6 dB. This was the first integration of balanced detectors with high-power, high-speed distributed photodetectors for high performance RF photonic links.

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