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Distributed Balanced Photodetectors for High Performance RF Photonic Links

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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) [1]. Because balanced photodetectors can achieve shot noise-limited link performance, the noise figure and spurious-free dynamic range of the link continue to be improved 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. 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 [2]. Compared with other photodetector structures, the VMDP is more suitable for implementing the balanced photodetection since it has separate optical and microwave waveguides. Here, we demonstrate a novel distributed balanced photodetector that can achieve high saturation photocurrent and large bandwidth simultaneously. A 3-dB frequency of 16 GHz and a responsivity of 0.64 A/W have been achieved.

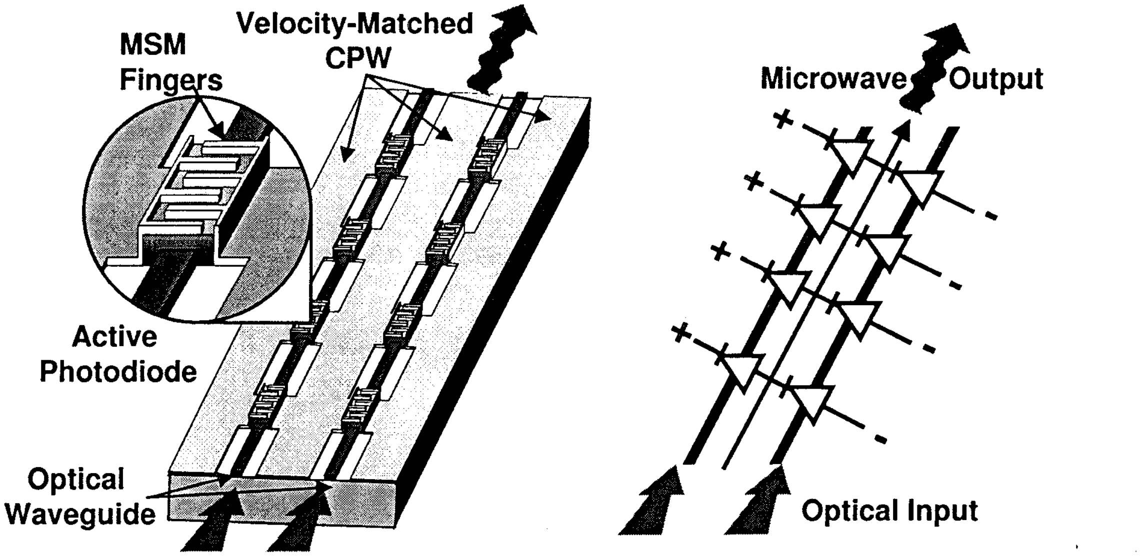

Figure 1. Schematic structure of the distributed balanced photodetector. The inset shows the active region with an MSM photodiode. Figure on the right shows the photodiodes connected to the optical waveguide in balanced detection mode.

Figure 1 shows the schematic of the balanced distributed 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 50Ω coplanar waveguide (CPW) output transmission line. Beam propagation simulation results indicate no crosstalk between the parallel optical waveguides, and the absorption per photodiode and the optical coupling loss between photodiodes are 8.8% and 3.2%, respectively. The diodes are 23 μm long and 5 μm wide. The MSM fingers 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 finger overlap of 10.5 μm is designed to provide the required capacitance loading for velocity matching. The matching ensures broadband operation. Unlike previously reported slow-wave CPW [3] that ignored the resistance of the MSM photodiode

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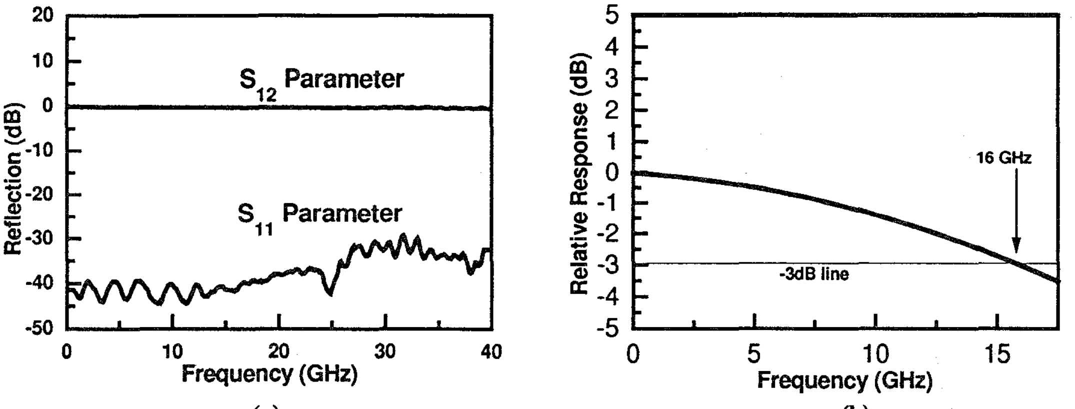
fingers, finite metal thickness and transmission line discontinuities in their quasi-static calculations, we used a full-wave analysis to achieve the velocity and impedance matching.

The unique advantage of the receiver is that it has monolithically integrated two high power distributed photodetectors with a velocity-matched 50Ω CPW. Most of the reported integrated balanced receivers suffer from low saturation power and are not suitable for analog links. In our design, the absorbing layer is designed to be on the top surface and evanescently coupled to a large-core passive waveguide. As the MSM photodiodes always remain below saturation by coupling only a small portion of the light from the passive waveguide, the receiver has the potential of exceeding the existing saturation photocurrents of conventional balanced photodetectors.

The dark currents of the balanced VMDP is minimized by passivating the mesa walls and placing the MSM finger tips above a silicon nitride layer [4]. The dark current of individual diode is measured to be below 0.5 nA, which is almost equal to the theoretically calculated dark current level. By coupling light directly from a lensed fiber to the waveguide facet of the receiver, the DC responsivity was measured for several different voltages and found to vary from 0.05 to 0.45 A/W as the diodes are biased from 0.5 volts to 8 volts. With anti-reflection coating, the responsivity at 8 V can be increased to 0.64 A/W.



(a) (b)

Figure 2. (a) The Measured S parameters of the CPW. (b) Frequency response of the balanced VMDP when only one waveguide is illuminated.

An HP 8510C network analyzer was used to measure the characteristic impedance and the microwave return loss (S_{11}) of the balanced receiver. Figure 2 (a) shows the S parameters of the loaded CPW. The characteristic impedance of the receiver is very well matched to 50Ω. The S_{12} is almost zero, ensuring a smooth transmission without loss. S_{11} is as low as -30 dB from DC to 40GHz. The experimental results verify the design for impedance matching.

The frequency response of the balanced VMDP was first characterized with light coupled to one waveguide only. Using optical heterodyne technique with two external cavity tunable lasers at 1.55 μm, the frequency response was measured and the 3-dB bandwidth was found to be 16 GHz. The bandwidth is currently limited by the carrier transit time of the MSM photodiodes with 1μm finger spacing. Since our bandwidth of the capacitance loaded CPW is much greater than 40 GHz (Fig. 2(a)), the bandwidth of the balanced VMDP can be increased by scaling down the MSM photodiodes. Theoretical simulation indicates that bandwidth > 100 GHz is achievable.

Figure 3 depicts the experimental setup for balanced detection. A distributed feebback laser with wavelength of 1542 nm is employed as optical source. The output 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, which produces two complimentary outputs for the balanced VMDP. The outputs were coupled to the VMDP by two single mode lensed fibers individually held by two silicon V-grooves separated by 140 μm. Since the accuracy of cutting optical fiber lengths is about 1 mm [5], a variable delay line was used to ensure equal optical path lengths between the two fibers, which is necessary to produce the broadband 180°

out-of-phase RF signals for balanced VMDP. The output from the balanced VMDP was measured using a spectrum analyzer.

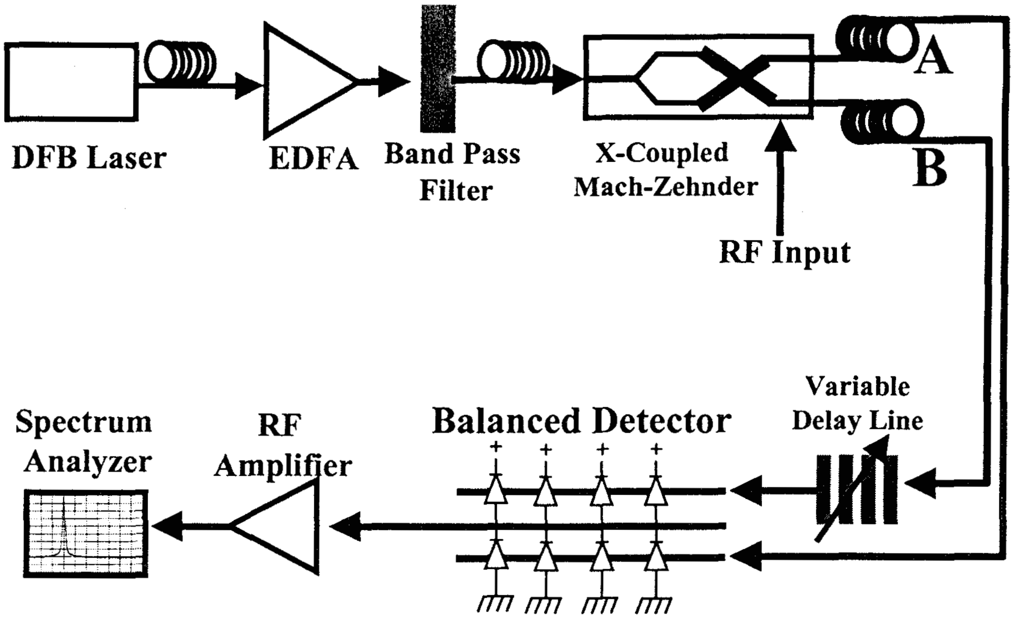
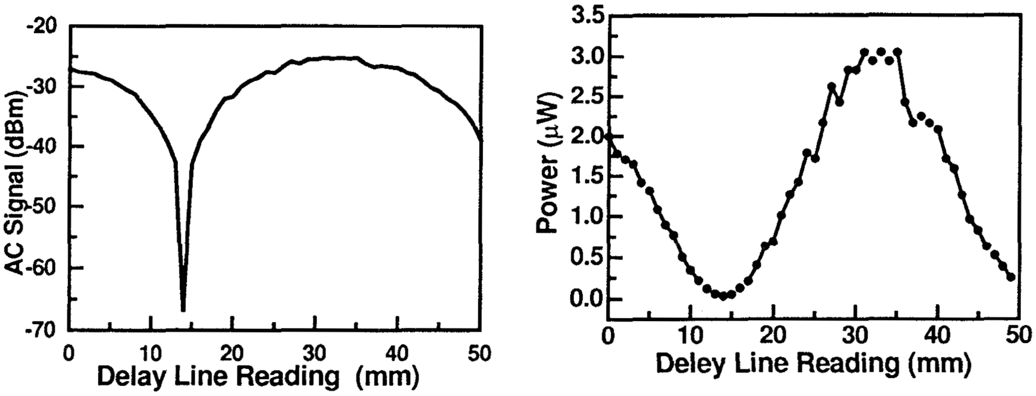


Figure 3. Balanced detection setup. The complimentary input signals are produced by the X-coupled MZ modulator.

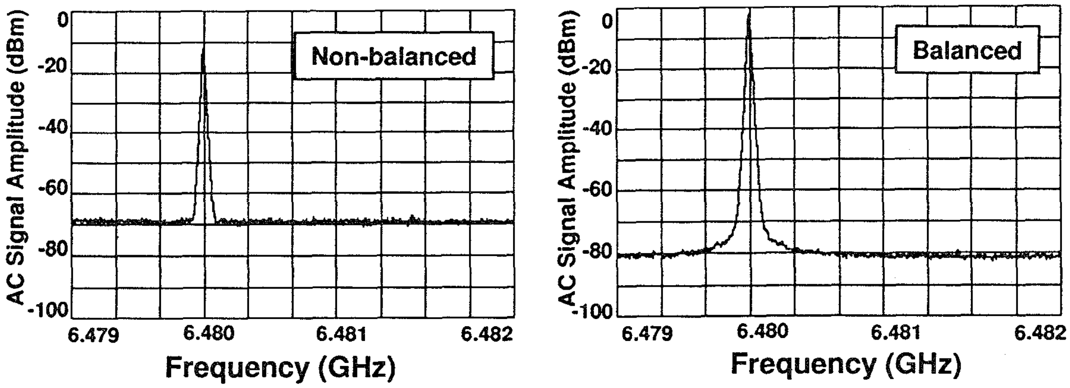
The device was biased in balanced mode by biasing one of the ground electrodes of the CPW at 8Volts. We used a custom made probe with integrated DC-blocking capacitor on the ground that connects to the CPW ground biased at higher voltage. To verify the balanced detection, we modulated the optical input at 8GHz and tuned the fiber optic delay line from 0 to 5mm delay. Figure 4 shows the RF signal verses 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 ration is more than 44dB.



(a) (b)

Figure 4. (a) 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. (b) The same plot in linear scale.

Figure 5 shows the RF spectrum of the output from the balanced VMDP in the non-balanced (only one waveguide is illuminated) and balanced mode. Suppression of the noise floor by 12-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. Typical balance between the VMDP was within 2% of the total photocurrent reading, which was limited to 2 mA in our preliminary experiments. For bandwidths lower than 6 GHz, the fiber length for one RF period is longer than 5 mm, the maximum delay length in our current setup. We are currently working on a new setup with two fiber delay lines to achieve exactly equal optical path lengths for broad band operation without any tuning of the delay line. This will allow us to measure the AC responsivity of the device in balanced mode.



(a) (b)

Figure 5. The AC signal in non-balanced (a) and balanced (b) detection modes are plotted separately. The balanced output is almost 6-dB higher in amplitude than the non-balanced signal. Preliminary results show a noise suppression level greater than 12-dB.

In conclusion, a balanced velocity-matched distributed photodetector (VMDP) with both impedance and velocity matching has been designed and successfully fabricated. Preliminary experimental results shows that the relative intensity noise has been suppressed by 12-dB, and the signal has been enhanced by 6-dB. This was the first integration of high power and high speed balanced detectors with a slow microwave transmission line to be used in high performance RF photonic links.

Acknowledgment

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