High-speed high-power traveling wave distributed photodetectors with backward wave cancellation

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ABSTRACT

The increased absorption volume of traveling wave distributed photodetectors can be used for high power generation without bandwidth reduction. In these traveling wave photodetectors, in order to not be limited by round-trip bandwidth limit, half of the generated photocurrent, which is traveling towards the input end, has to be absorbed in an input termination. We propose cancellation of the backward propagating current by using a multi-section transmission line to eliminate this loss. The impedances of the individual transmission line sections are chosen such that the backward current (traveling towards input end) generated by each of the diodes is canceled by the reflected fraction of the forward current (traveling towards output end) generated by the preceding diodes. With backward wave cancellation, RF response increases by up to 6dB while maintaining high-bandwidth. We present here the experimental results of a traveling-wave-backward-wave-cancelled photodetector with 38GHz bandwidth and up to –1dBm of linear RF output at 40GHz.

Keywords: Traveling wave photodetectors, velocity matched photodetectors, backward wave cancellation, distributed photodetectors, high-power photodetectors, coplanar transmission line, microwave photonics

1. INTRODUCTION

High-power, high-speed photodetectors reduce RF insertion loss, increase spurious free dynamic range and signal-to-noise ratio of analog fiber optic links1. Increasing the absorption volume increases the responsivity and maximum linear saturation power. The absorption volume can be increased beyond the RC time constant limit of single, lumped photodetectors, by making the diode contacts transmission lines in traveling wave photodetectors (TWPD) 2,3. Bandwidth in TWPD is limited by phase walk-off due to mismatch between the optical and microwave velocities. Velocity matched distributed photodetectors (VMDP), in which the periodic capacitance of the distributed diodes is used to match the microwave and optical velocities, have demonstrated high saturation current by increasing the total absorption volume while adding up the electrical signal from the individual photodiodes in phase to achieve high bandwidth 4,5. In both TWPD and VMDP, the input end needs to be terminated with the line impedance (usually 50Ω), otherwise, the phase lag between the currents traveling directly to the load and the reflection of currents traveling toward the input will decrease the bandwidth. The bandwidth improvement with input termination is, however, at the expense of efficiency as half of the current generated by the individual photodiodes is dissipated in the input 50Ω termination. The RF response can be
improved by canceling out the backward propagating wave using a multi-section transmission line, as originally proposed for distributed amplification in traveling wave tubes. A similar scheme for improving the efficiency of traveling wave distributed photodetectors has been proposed by. In this paper, we report the first experimental demonstration of a multi-section transmission line traveling wave distributed photodetector (MS-TWDP) with dissimilar coplanar strips (CPS) for backward wave cancellation (Figure 1). The line impedances of the different sections are designed to cancel out the backward propagating wave and thus improve RF response without degrading bandwidth. We have achieved 3dB bandwidth of 38GHz and up to –1dBm of linear 40GHz RF output power in our photodetectors.

2. THEORY

The backward propagating wave in any traveling wave device can be cancelled through a multi-section transmission line. The line impedances of the different sections are chosen such that the reflected portion of the forward propagating current is cancelled out by the fractional current which flows in the reverse direction due to current division (by Ohm’s law) as shown in Figure 2, where $\beta$ is the current fraction due to Ohm’s law and $\Gamma$ is the reflection coefficient at the transmission line discontinuity. By equating the two backward traveling currents, viz., $\beta I_{n+1}$ and $\Gamma I_n$, we can derive the following expression for the line impedances in the $n^{th}$ and $n+1^{th}$ sections adjoining current source $I_n$.
where $Z_n$ and $Z_{n+1}$ are the transmission line impedances of the $n^{th}$ and $(n+1)^{th}$ sections (looking from the input end). In the case when the currents in all the $n$ sources are the same, Eq. 1 reduces to

$$Z_n = \frac{Z_{n+1}}{n}$$

In Eq. 2, $Z_n$ is the line impedance of the $n^{th}$ section looking in from the input end and $Z_f$ is the impedance of the first section. Equal distribution of photocurrents among the different diodes can be achieved through parallel feed using a monolithically integrated multimode interference coupler (MMI) coupler $^9$. In this work, however, we use series optical feed and tailor the diode lengths to get the required photocurrents as detailed in the following section.
3. DESIGN

The first step is to choose the number of diodes in the distributed detector and the fractional current generated in the individual diodes. In an evanescently coupled waveguide photodetector, increasing the number of diodes increases the responsivity of the photodetector along with the line impedance of the first segment of the transmission line per Equation 2. The limit for the number of photodiodes is thus set by the maximum line impedance that can be fabricated and microwave losses of the skinniest (highest impedance) line.

As for selection of the current distribution, we would ideally like to have equal currents in the individual photodiodes so that the high power generation is not limited by thermal failure of the first diode 10.

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>p++ In_{0.53}Ga_{0.47}As; t=20nm</td>
<td></td>
</tr>
<tr>
<td>Graded p InGaAsP (λ=1.32µm); t=0.2µm</td>
<td></td>
</tr>
<tr>
<td>i setback and Graded layer I; t=80nm</td>
<td></td>
</tr>
<tr>
<td>i-absorption; In_{0.53}Ga_{0.47}As; t=0.2µm</td>
<td></td>
</tr>
<tr>
<td>i setback, Graded Layer II and InP stop etch; t=100nm</td>
<td></td>
</tr>
<tr>
<td>n++ InGaAsP (λ=1.42µm); t=0.25µm</td>
<td></td>
</tr>
<tr>
<td>undoped InGaAsP (λ=1.42µm) undoped; t=0.15µm</td>
<td></td>
</tr>
<tr>
<td>i-InP; etch stop; t=10nm</td>
<td></td>
</tr>
<tr>
<td>undoped InGaAsP (λ=1.06µm); t=1.3µm</td>
<td></td>
</tr>
</tbody>
</table>

Substrate InP

Figure 3: Epitaxial structure of the MS-TWDP

In this work, we chose three diodes and equal current distribution among them. The required line impedances of the individual sections of the multi-section transmission line are thus 150Ω, 75Ω and 50Ω (Equation 2) from input to output. The widths of the coplanar lines are 2µm, 40µm and 120µm and the separations are 120µm, 100µm and 60µm respectively. The spacing between the diodes is 300µm.

1.1. Epi-layer design

In a series feed photodetector, the maximum linear photocurrent is limited either by thermally induced failure or due to charge screening due to high photocurrent densities. In either case the entire photodetector ends up being limited by the worst case among the individual diodes. Equal photocurrents and photocurrent densities can be obtained through parallel feed of the diodes with an integrated multimode interference (MMI) coupler 9. The MMI coupler however increases the
size of the photodetector. In this work we decided to achieve equal photocurrents by tailoring the lengths of the photodiodes. In addition, we use a matching layer. The extension of the matching layer beyond the diode can be designed for high responsivity \(^{11}\) or for high-linearity by making the photocurrent density more uniform \(^{12}\). The diode lengths of the diodes in our photodetector are 8\(\mu\)m, 10\(\mu\)m and 20\(\mu\)m respectively. The matching layer extension is chosen to be 18\(\mu\)m to make the photocurrent density more uniform.

![Fabrication Process Diagram](attachment://fabrication_process_diagram.png)

Figure 4: Key steps in the fabrication sequence of the MS-TWDP

The epitaxial layer shown in Figure 3 consists of a 0.4\(\mu\)m thick, Q1.42\(\mu\)m matching layer between a 1.3\(\mu\)m thick, Q1.06\(\mu\)m core and a 0.2\(\mu\)m thick lattice matched InGaAs absorbing layer. Zn doping in the 0.2\(\mu\)m Q1.3\(\mu\)m InGaAsP cap is graded to prevent Zn diffusion into the absorbing region. The setback layers on either side of the absorbing region are also graded to reduce carrier trapping and increase bandwidth. Only half of the matching layer is Si-doped to form the n-contact layer to reduce optical losses in the passive waveguide.

### 4. DEVICE FABRICATION

The fabrication process, as shown in Figure 4 begins with a 4\(\mu\)m active mesa being selectively wet-etched using H\(_2\)SO\(_4\):H\(_2\)O\(_2\):10H\(_2\)O. The n-contact mesa-cum-matching layer is then patterned using the same H\(_2\)SO\(_4\):H\(_2\)O\(_2\):10H\(_2\)O etchant. The p-contact is patterned on the active mesa by evaporating 200A AuZn / 300A Ti / 2000A Au in an e-beam evaporator followed by conventional photoresist liftoff in acetone. The 12 \(\mu\)m wide passive waveguides are patterned by
time etching 0.7µm of the Q1.06µm InGaAsP with HCl:HNO₃:H₂O. 5000Å of SiN is then deposited at 325°C using a PECVD machine for passivating the photodiodes. Openings are patterned in the passivation nitride for the n-contact and interconnect metal. The n-metal is also used for the interconnect metal to save a processing step. 50Å Ni/ 1000Å AuGe/

Figure 5: Scanning electron micrograph of a fabricated MS-TWDP showing the multi-section coplanar transmission line connecting the individual photodiodes

Figure 6: DC responsivity measurement. DC photocurrent is linear up to 12mA at –4V bias
1000Å Ag/2000Å Au is then evaporated using e-beam evaporator and lifted-off. The contacts are finally annealed using an RTP system at 380°C for 10s. Scanning electron micrograph (SEM) of one of the fabricated devices is shown in Figure 5.

5. RESULTS AND DISCUSSION

The DC responsivity of the MS-TWPD is 0.24A/W (Figure 6). The responsivity is limited by losses at the waveguide-photodiode interface, fiber coupling loss into the optical waveguide and imperfections in the AR coating. A significant fraction (which is calculated to be ~15% per diode using commercial BPM software) of the input light is lost into radiation modes during coupling between the passive waveguide to the photodiode and back from the photodiode into the passive waveguide. In order to reduce this waveguide-photodetector transition loss, we could use an MMI coupler to generate equal photocurrents among the individual photodiodes⁹. The excess loss of the MMI can be less than 1dB as shown in ¹³. The dark current is typically less than 100nA per diode and a ~2V bias is sufficient to completely deplete the absorption layer. The DC responsivity, shown in Figure 6, remains linear up to 12mA at which point the photodetector fails due to thermally induced failure of the first diode due to small inequalities in the currents generated in the individual photodiodes. After failure, the detector responsivity is decreased by ~30%. The heterodyne frequency measurement setup used for bandwidth and RF linearity measurements is shown in Figure 7. Two Photonetics external cavity diode lasers are mixed to generate the RF signal. The output of the 3dB coupler is amplified in an SDL FA30 erbium doped fiber amplifier (EDFA). The amplified output of two tunable lasers is controlled using an attenuator and then coupled into the MS-TWDP using a lensed fiber. A 5nm optical bandpass filter is used to reject out of band optical power from the

![Figure 7: Schematic of setup used for bandwidth and RF linearity measurements](image-url)
EDFA output. The generated RF signal is collected by probing the 50Ω section of the MS-TWDP with a 40GHz GGB Industries picoprobe and measured in a HP8487A power sensor-power meter. The RF frequency is monitored throughout the measurement using the HP8565E RF spectrum analyzer. The measured RF power increases quadratically with the input optical power.

The frequency response measured at 0dBm input optical power and ~2V bias (Figure 8) shows that the 3dB bandwidth is 38GHz. It should be mentioned that the frequency response of the probe which, per specifications, has a loss of ~1dB at 40GHz has not been calibrated out of this measurement. Inspite this, the measured bandwidth is ~2.5 times higher than the round trip time bandwidth limit of ~15GHz. Backward wave cancellation thus enables us to achieve high bandwidth in traveling wave distributed photodetectors while increasing the RF response by up to 6dB. With backward wave cancellation, the necessity of fabricating an on-chip termination resistor and low frequency roll-off from the input end DC block capacitor (which needs to be fabricated at the input end along with the resistor to reduce dark current) are eliminated. Measurement of the linearity of the RF response at 40GHz is shown in Figure 9. At a bias of ~2V, the 40GHz RF response compresses by 1dB at ~5dBm. When the bias voltage is increased to ~3V, the 1dB compression power increases to ~1dBm. When the bias was further increased to ~4V, the first diode of the detector failed (indicated by the photodetector responsivity decreasing by 30% and the photodetector continuing to function at this lowered responsivity). The failure is due to thermal dissipation induced break of the interconnect metal from the diode contacts. With improved heat sinking we expect to achieve even higher linear RF powers.

Figure 8: Frequency response of the MS-TWDP. The 3dB bandwidth is 38GHz

![Frequency response graph](image-url)
6. CONCLUSION

Losses in the input termination of TWDP can be eliminated by canceling the backward propagating wave, using the reflections at the discontinuities in a multi-section transmission line. The RF responses increased by up to 6dB without any bandwidth degradation. We have demonstrated backward wave cancellation in traveling wave distributed photodetectors using a multi-section coplanar strip line. The 3dB bandwidth in our 600µm long detector is 38GHz without using any input termination. Our highly linear photodetector also shows 12mA of linear DC photocurrent and up to -1dBm of linear 40GHz output.

7. ACKNOWLEDGEMENT

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8. REFERENCES


