TRAVELLING-WAVE PHOTODETECTORS

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Abstract

Attention to the microwave design of waveguide photodetectors leads to travelling-wave photodetectors. These devices show bandwidths as high as 172 GHz, the highest reported for a p-i-n photodetector, and bandwidth-efficiency products as large as 76 GHz, the largest reported for any photodetector without gain. Direct comparisons with vertically illuminated and waveguide photodetectors confirm the advantages of travelling-wave photodetectors.

Background

The concept of the travelling-wave photodetector (TWPD) was first presented in 1990 as a means to overcome the bandwidth-efficiency limits of conventional photodetectors [1]. Both p-n and Schottky junctions were briefly mentioned, although the several designs listed in the proposal were of the metal-semiconductor type. The use of doped layers generally results in a slow-wave structure, however in 1991, a proposal for a velocity-matched p-i-n TWPD was announced [2]. The basic theory of TWPDs, quantifying the velocity mismatch impulse response and associated bandwidth limitations, was detailed in 1992 [3]. The first experimental demonstration of TWPDs was published in 1994 [4].

The TWPD is based on the waveguide photodetector (WGPD), which has a greater potential bandwidth-efficiency product than is achievable with conventional, vertically illuminated photodetectors (VPDs). The illumination is guided perpendicular to the carrier drift field, allowing a long absorption path while maintaining a small junction area, so the interdependence of bandwidth and internal efficiency is reduced.

High external efficiency then depends on coupling most of the light into the waveguide, which can be accomplished by appropriate design of the device layers [5] or by the use of separate input waveguide segments [6-8]. These types of structures maintain their performance over a broad optical bandwidth and wide temperature range, and they are well-suited for inclusion of an integrated semiconductor optical preamplifier [9].

Mushroom-mesa WGPDs have yielded 110 GHz bandwidth with 50% quantum efficiency [10]. This 55 GHz bandwidth-efficiency product is much greater than the inherent VPD single-pass limit of about 30 GHz. The structure of these devices does not support propagation of the electrical response to the load without reflection, so they are described by a lumped element model that leads to an RC bandwidth limitation [11]. Even higher bandwidth-efficiency products are possible with consideration for the propagation of the electrical waves to the load.

Theory

TWPDs are designed to support travelling electrical waves with specified characteristic impedance [3]. A TWPD is a terminated section of transmission line with an exponentially decaying photocurrent source propagating on it at the optical group velocity. The termination at the output end is defined to match the characteristic impedance of the photodetector.

The travelling current source produces current waves that propagate in forward and reverse directions. The reverse wave is reflected at the device input end. Fig. 1 depicts the propagation of forward and reverse wave photocurrent impulse responses on a TWPD of length ℓ. The speed and characteristic impedance of these electrical waves are generally very low because the electric fields are confined to a thin layer while the modal currents are carried in relatively remote conductors. Mismatches between the optical group velocity, v_o, and electrical phase velocities, $\pm v_e$, distort the electrical response, the effect being greater for the reverse-travelling wave.

The photocurrent impulse response due only to velocity mismatch is a double-exponential waveform given by

$$i_{vm}\left(t+\frac{\ell}{v_e}\right)=\frac{Q}{2}\left[\left|\omega_f\right|e^{\omega_f t}\mathrm{u}\left(-\omega_f t\right)+\gamma\omega_r e^{-\omega_r t}\mathrm{u}(t)\right] \quad (1)$$

for $\min(\ell/v_o, \ell/v_e) \le t \le \ell/v_o + 2\ell/v_e$ and zero elsewhere. $\omega_f = \Gamma\alpha v_e/(1 - v_e/v_o)$ and

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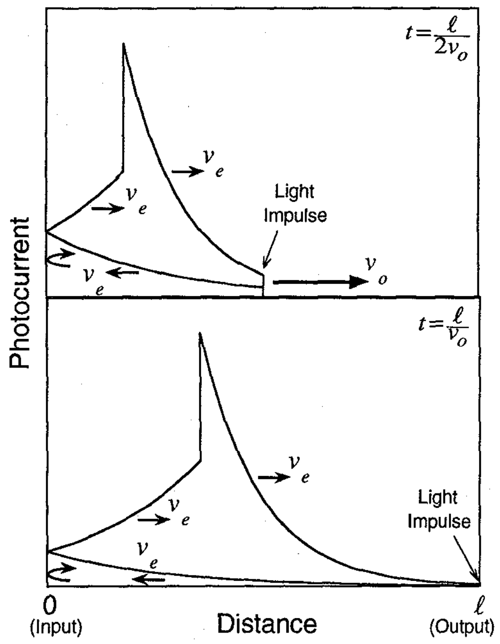

Fig. 1. Propagation of photocurrent impulse response on a TWPD showing velocity-mismatch effects.

$\omega_r = \Gamma\alpha v_e/(1+v_e/v_o)$ are characteristic frequencies of the forward and reverse waves. Q is the total charge generated by the optical impulse, Γ is the optical confinement factor, α is the optical absorption coefficient, γ is the electrical reflection coefficient at the device input end, and u is the unit step function.

A matching termination at the input end of the TWPD ($\gamma = 0$) increases its bandwidth. However, the bandwidth is still limited by other factors, and the dissipation of half of the photocurrent in this resistor will likely result in a worse bandwidth-efficiency product than if the input were left unterminated [3].

It can be shown that the velocity-mismatch bandwidth limitation for a long TWPD ($\Gamma\alpha\ell >> 1$) with open-circuit input termination ($\gamma = 1$) is approximated by

$$B_{vm} \approx \frac{\Gamma\alpha v_e}{3\pi} \tag{2}$$

with less than 6% error over the entire range of velocities from completely mismatched to beyond matched, $0 \le v_e/v_o \le 1.47$. Increasing the electrical velocity increases the velocity-mismatch bandwidth limitation, but velocity-matching is surprisingly of almost no direct value. In fact, the mismatched case, where $v_e/v_o > 1$, is preferable to the matched case, $v_e/v_o = 1$.

By assuming quasi-TEM propagation on the TWPD, Eq. (2) can be cast in a more familiar form,

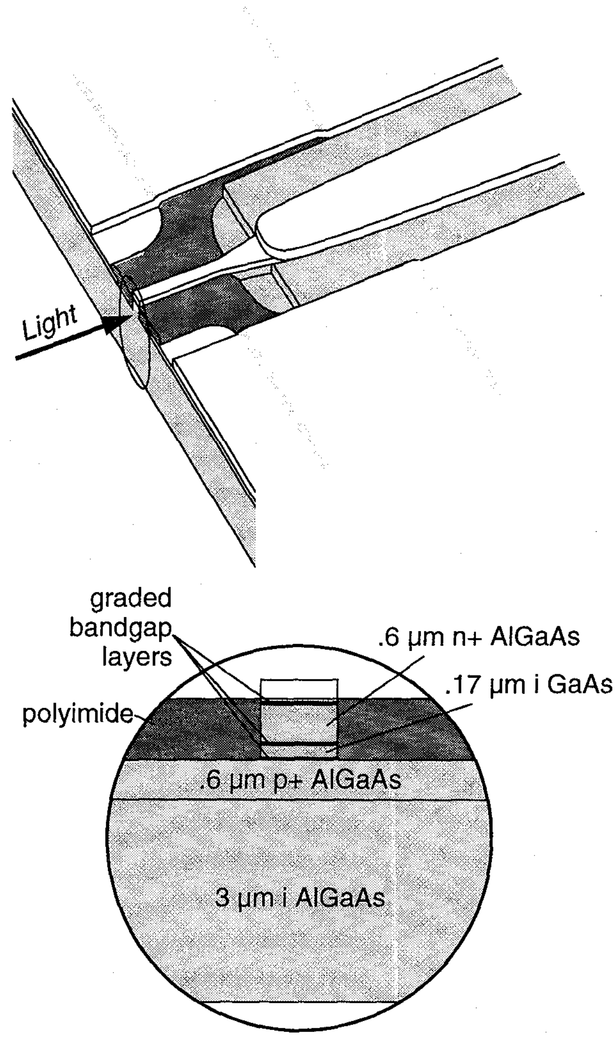

Fig. 2. Hybrid-coplanar TWPD structure and epitaxy.

$$B_{vm} \approx \frac{1}{2\pi Z_0}\frac{\Gamma\alpha}{1.5C} \tag{3}$$

where Z_0 and C are the transmission line characteristic impedance and capacitance per unit length. Evidently, the TWPD velocity-mismatch bandwidth limitation is comparable to the RC bandwidth limitation for a WGPD of fixed length, $\ell = 1.5/\Gamma\alpha$, even though the TWPD is physically much longer. Thus, the TWPD is capable of simultaneously delivering large bandwidth and high efficiency.

Experiment

TWPDs, WGPDs, and VPDs were fabricated on the same wafer for direct comparisons of their performance [4, 12]. All devices interface with 50 Ω coplanar waveguide transmission lines.

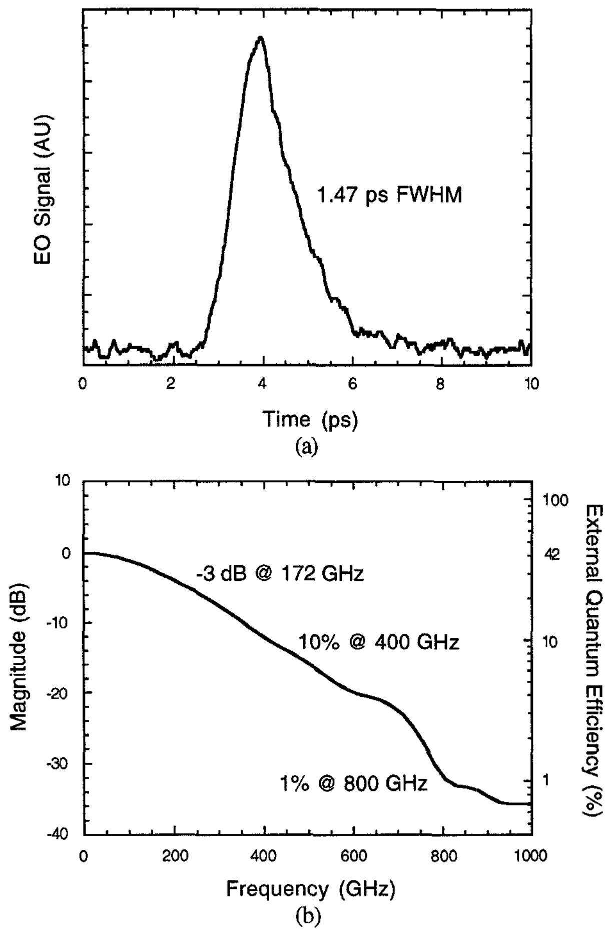

Fig. 3. Measured (a) pulse response and (b) corresponding electrical frequency response of a TWPD.

The hybrid-coplanar TWPD structure, drawn in Fig. 2, has qualities of microstrip and coplanar waveguides. The waveguide is designed such that the nominally 1 μm wide TWPD has a characteristic impedance of about 50 Ω, and it has an open-circuit termination at the input end. The double heterostructure eliminates carrier diffusion contributions to the response resulting from photogeneration in low-field regions, and graded bandgap layers minimize carrier trapping at the hetero-interfaces [13].

The WGPDs are identical in structure to the TWPDs except that they are 2 μm or 5 μm wide. Their characteristic impedances are much less than 50 Ω, resulting in large impedance mismatches between the WGPDs and the transmission lines.

Fig. 3(a) shows the 1.47 ps full-width at half-maximum pulse response of a 7 μm long TWPD measured by pump-probe electro-optic sampling [14]. The electrical frequency response from the Fourier transform (Fig. 3(b)) has a 3 dB bandwidth of 172 GHz. The external quantum efficiency is greater than 10% at 400 GHz and 1% at 800 GHz. A bandwidth-efficiency product of 76 GHz was measured for this device.

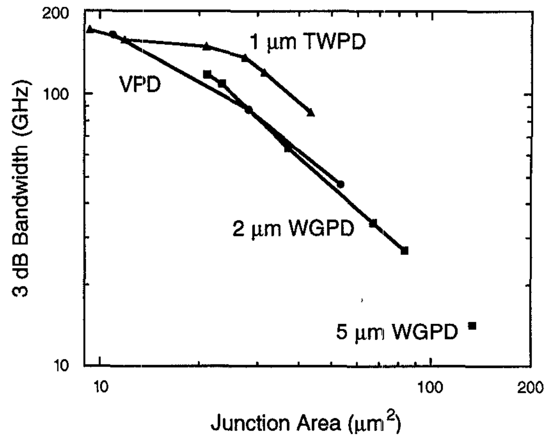

Fig. 4. Bandwidths vs. junction areas of travelling-wave, waveguide, and vertical photodetectors.

A 2 x 9 μm^2 WGPD has a bandwidth of 118 GHz and bandwidth-efficiency product of 57 GHz. These are the highest values reported for a WGPD, but the TWPD bandwidth-efficiency product is still 1/3 greater. A 3 x 3 μm^2 VPD has a bandwidth of 165 GHz, but its internal quantum efficiency is limited to about 30%.

To show that the TWPD bandwidth is not bounded by an RC limitation determined by the total junction area, the bandwidths of various lengths of TWPDs and WGPDs and various sizes of VPDs are plotted versus junction area in Fig. 4. All of the device bandwidths approach the transit-time bandwidth limitation as the area becomes small. The bandwidths are inversely proportional to area for larger (or longer) devices, but the bandwidths of the TWPDs are 50% larger than those of the WGPDs or VPDs. This demonstrates that the TWPD is not subject to the same RC bandwidth limitation as the lumped devices.

The bandwidth limitations associated with photodetection affect a TWPD response only where there is light absorption. After the light is mostly absorbed, the response is dominated by the electrical wave propagation characteristics. The decrease in bandwidth with increasing TWPD length can then be attributed to microwave loss on the metal-clad p-i-n waveguide structure.

The responses of long TWPDs vary only by the effects of propagation over the differences in their lengths. Thus, the complex microwave propagation constant can be determined by deconvolving the responses of long TWPDs. This method is equivalent to finding the propagation constant from network analyzer measurements of different lengths of transmission line. Fig. 5 shows the TWPD microwave field attenuation constant, deconvolved from pulse response measurements. The attenuation is proportional to f^2 for frequencies below about 75 GHz, and it is dominated by an $f^{1/2}$ dependence from 75 GHz to 150 GHz.

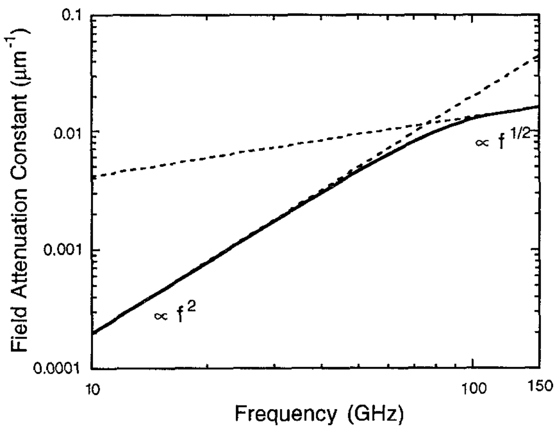

Fig. 5. TWPD microwave field attenuation constant from pulse response measurements.

Summary & Conclusions

In summary, travelling-wave photodetectors are not subject to an RC bandwidth limitation in which the capacitance depends on total junction area. Increasing the electrical velocity improves the bandwidth, while matching electrical and optical velocities has little effect. Travelling-wave photodetectors hold the records for bandwidth of a p-i-n photodetector and bandwidth-efficiency product for any photodetector without gain, and they show external quantum efficiencies as high as 10% at 400 GHz and 1% at 800 GHz. Although microwave loss limits the bandwidths of longer devices, travelling-wave photodetectors are clearly superior to vertically illuminated and waveguide photodetectors.

Acknowledgements

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