High-Speed Photodetectors

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Abstract: The paper highlights recent developments of high-speed photodetectors for 200 Gb/s and beyond communication applications. Designs for standard photodiode types as well as avalanche photodiode types with internal amplification are reviewed in terms of their high-speed performance.

1. Introduction

From a commercial perspective, the capital expenditure of optical frontends can be roughly halved, when doubling the symbol rate, because only half the number of transceivers are required. For this reason, a trend towards higher symbol rates can be observed. While 100 GBaud transmission schemes are going to be standardized soon [1], recent publications already show transmission experiments with high symbol rates up to 200 GBaud for coherent and direct detection schemes [2,3]. These experiments are enabled by the availability of high-speed components [4-7]. The high-speed components are mandatory for reducing the operational expenditure, because less DSP computation with its high power consumption is needed, for compensating the decreased signal performance of components with lower speed.

This manuscript will review recent results of photodetectors for data- and telecom applications, operating in the O- to L-band wavelength range. As a result, possibilities on how to align recent photodetector developments with the trend for high symbol rates are discussed.

2. Standard PIN and UTC Photodetectors

For efficient data transmission with low power consumption at the transmitter side, photodetectors with high quantum efficiency from the fibre output up to the conversion inside the photodiode are required. An option to improve the quantum efficiency for vertically illuminated photodiodes is, to increase the absorber thickness, which in turn limits the speed of the photodiode due to longer carrier transient times. This tradeoff between responsivity and bandwidth is one of the key performance parameters for high-speed photodetectors. To get beyond the limitation of vertically illuminated photodiodes, waveguide integrated photodiodes were introduced, decoupling the tradeoff between absorption and transit time. Fig. 1 shows state of the art high-speed photodetectors. The trend lines show that at approx. 42 GHz the performance becomes better for waveguide integrated photodetectors compared to vertically illuminated photodetectors.

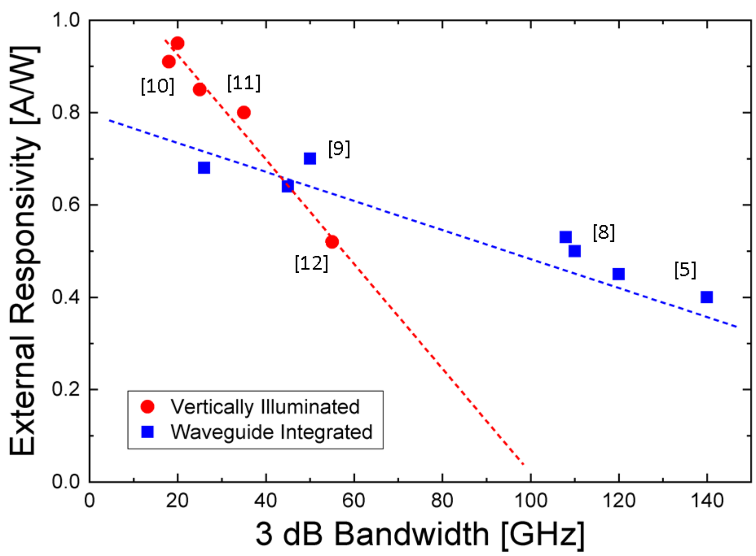

Fig. 1. Responsivity vs. 3 dB bandwidth for state of the art photodetectors at 1550 nm of wavelength; the responsivity is defined as external responsivity coupling to an SMF

Currently two sophisticated material platforms are used for designing photodetectors in the O- to L-band wavelength range: Ge/Si and InGaAs/InP. Since growing thick Ge layers on Si results due to the lattice mismatch between Si and Ge in stress and defects, the dark current increases for thick absorbers of vertically illuminated photodetectors in the Ge/Si material system. For this reason, most of the vertically illuminated photodetectors are realized in the InGaAs/InP material system. Regarding the waveguide integrated photodetectors, efficient light coupling from the fiber into the waveguide and from the waveguide into the photodiode needs to be implemented. So far, for most of the silicon photonics platforms the light is still coupled with grating couplers from the fiber into the waveguide. As a result, the quantum efficiency of the photodetectors is reduced, reducing the efficiency of the whole transmission system. Therefore, Fig. 1 is dominated by InGaAs/InP material solutions for both photodetector types.

According to the rule of thumb that the photodetector 3 dB bandwidth should be approx. 0.7 times of the symbol rate, a 140 GHz photodetector would be suitable for 200 GBaud. Current design challenges for the high-speed devices are besides of a high external responsivity, to overcome limitations of the RF performance being related to the photodiodes RC low-pass characteristic. The RC issue is caused by thin absorber layers, being due to the reduced transit time of waveguide integrated photodiodes. Uni-travelling carrier (UTC) photodiode types partly solve the issue by introducing a collector layer, being only crossed by fast electrons [13]. Furthermore, for evanescently coupled photodiodes, the light has to couple through the low refractive index collector layer, decreasing the optical coupling efficiency from the waveguide to the photodiode. For this reason, flipping the photodiode layer stack [14] helps to overcome the issue.

3. Avalanche Photodiodes

Avalanche photodiodes (APD) are applied for direct detection data center interconnects. Due to the internal amplification of APDs, the detector sensitivity is increased, helping to decrease the interconnects power budgets. While for standard photodetector types, the InGaAs/InP material system shows advanced performance compared to Si/Ge material system, for APDs also devices from the Si/Ge material system take an important role. The reason for the change is related to the k-ratio of the multiplier material, being an important parameter for the APD bandwidth [15]. The k-ratio of Si is better compared InAlAs, being commonly used multiplier materials for Ge/Si and InGaAs/InP material platform, respectively.

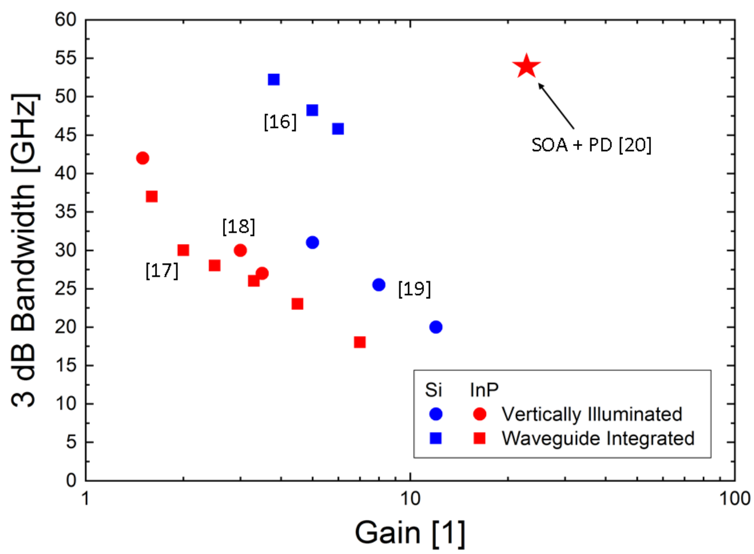

Fig. 2. GBP representation for state of the art avalanche photodiodes operating in the O- to L-band wavelength range (only InP-based devices with mentionable intrinsic external responsivity are included)

The typical figure of merit for APDs is the gain-bandwidth product (GBP). Fig. 2 represents the GBP for state of the art APDs of both material systems. According to the figure, the devices with Si-based multiplier show a better GBP compared to the devices with InAlAs-based multiplier. However, the GBP does not account for all important parameters, because the definition has been introduced more than a decade ago. At this time, devices had a high quantum efficiency due to the low-speed specification because of low data rates. For high-speed photodetectors, the external intrinsic responsivity at unity gain needs to be taken into account as well, in order to consider the interconnect power consumption. For the same reasons (fiber-to-waveguide coupling and growth of thick Ge-layers) as for the standard photodiode types in the previous section, the overall performance of the InGaAs/InP-based APDs improves. Hence, InGaAs/InP-based APDs are often used in data center interconnects. As a result, the GBP figure of merit needs to be extended, in order to proper represent recent high-speed APD developments. Multiplying the GBP with the external intrinsic responsivity will give a better representation of the APD performance.

Regarding the high-speed performance, current designs seem to be limited to approx. 56 GBaud symbol rate. New multiplier materials like Sb-based compounds could improve the k-ratio and therefore the APD bandwidth. Alternatively, the combination of an SOA in front of a photodiode helps to decouple the gain from the bandwidth. Recent publication show that for current symbol rates are above the interband effects of the SOA and allow for pattern- free detection of data signals [20,21].

4. Conclusion

Current photodetector developments are in line with the high-speed transmission experiment trends. Per today, symbol rates of 100 GBaud can be handled with devices being at TRL 7 to 8. For 200 GBaud, so far only test & measurements solutions are available.

Performing high symbol rate transmission experiments with low-speed components, results in additional DSP power consumption, for compensating worse RF-performance. In order to keep the power budget for optical interconnects low, the photodetectors need to have a proper RF transmission characteristic and external responsivity which have to be represented by the photodetectors figure of merit. Furthermore, the co-design of photodetectors and TIA electronics is important for optimized performance, when commercializing high-speed receivers for 200 GBaud interconnects.

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