Design and optimization of evanescently coupled waveguide photodiodes*

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Abstract: We present the design and optimization of evanescently coupled waveguide photodiodes (EC-WPDs) based on the coupling modes theory and the beam propagation method. Efficient focalization of the optical power in the absorber is achieved by an appropriate choice of index matching layers of EC-WPDs. Numerical simulation shows that high-speed (40 GHz), high quantum efficiency (81%) and high linearity photodiodes can be achieved, and EC-WPDs are promising devices for future optical communication systems.

Key words: photodiode; coupling modes theory; beam propagation method
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1. Introduction

Photodiodes (PDs) with high-speed, high quantum efficiency and high optical power handling capability are key components for future optical communication systems.

Side-illuminated waveguide PDs, where light and photogenerated carriers travel in perpendicular directions, have recently attracted extensive attention due to the independent optimization of internal quantum efficiency and bandwidth, which makes them able to obtain better performances than traditional surface-illuminated PDs. However, low coupling efficiency to single mode fiber and poor high-power capability of such waveguide PDs result in low external quantum efficiency, low saturation current and poor linearity[1]. To overcome these severe limitations, evanescently coupled waveguide photodiodes (EC-WPDs) have been proposed. In EC-WPDs[2], the light couples evanescently from the passive multimode waveguide to the photodiode mesa, which ensures more uniform absorption along the absorber length and leads to an improved high-power capability. Additionally, the use of multimode waveguide structures enlarges the optical field distribution, thus enhancing the coupling efficiency with the fiber.

Many groups have reported research on EC-WPDs[2−4], however, most of them were focused on experiments. The theoretical analysis and design of EC-WPDs, which can provide an efficient guide to designers, is rare. In this paper, we use the coupling mode theory[5] and the beam propagation method (BPM) to design and optimize EC-WPDs. The carrier transit time and resistance–capacitance (RC) time limits have been considered for realizing high speed operation. Numerical simulation results show that high external quantum efficiency (81%) and high speed (40 GHz) photodiodes can be obtained by optimizing the thickness and length of the matching layer.

2. Design and simulation of photodiode structure

The challenge of designing an EC-WPD is to achieve efficient optical coupling between the passive waveguide and the absorber. Thus, PD devices are able to absorb as much light as possible over such a short diode length. Figure 1 shows a schematic diagram of a conventional EC-WPD, including a diluted waveguide (DW) and a PIN heterojunction structure. A DW with a low refractive index is utilized for its high optical coupling efficiency with fiber, the absorbing layer is for light absorption and the match layer (ML) region is for better coupling efficiency between the DW and the absorber, which is essential in the design.

Through carefully consideration of the above three regions, PDs with high coupling efficiency, high quantum external efficiency (> 80%), high bandwidth (∼ 40 GHz) and

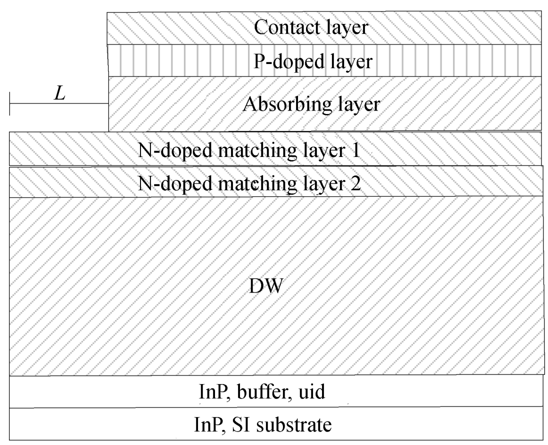

Fig. 1. Schematic diagram of a cross section of EC-WPDs.

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excellent high power capability are obtained.

2.1. Diluted waveguide

The DW is composed of periodic InP layers and thin InGaAsP quaternary layers to enlarge the distribution of the optical field. Thus the optical mode mismatch between the optical fiber and the waveguide is reduced and a high coupling efficiency is obtained. There are numerous literatures on the design of DWs considering the periodic number, layer thickness and layer refractive index[6]. A coupling efficiency of larger that 90% and a polarization dependence smaller that 1 dB are obtained through the three dimensional beam propagation method (3D-BPM)[7] in this work. The corresponding DW structure has 10 periods of 0.08 μm thick 1.1Q and 0.12 μm thick InP and 5 μm width. In this paper, we adopted the above DW structure in our device.

2.2. Matching layer

A ML generally consists of one or two InGaAsP layers with a refractive index between that in the DW and the absorbing layer. As the guided light reaches the PIN section, which incorporates the absorbing and DW layers, it is coupled in to several transverse modes. The beating of these modes causes the optical intensity distribution to oscillate between the passive waveguide and the absorber regions along the light propagation direction. The ML is used to enhance the optical coupling efficiency and mode oscillation between the DW and the absorbing layer. As a result, the optical intensity can be transferred into the absorber over a relatively short distance.

The thickness of the ML and the length of the input waveguide are very essential for the realization of a high performance of EC-WPD. Hence, it should be carefully considered. The coupling mode theory and BPM were used to design and optimize EC-WPDs.

The two parts of the passive waveguide, the DW and the ML, are regarded as a two-port directional coupler. In coupling mode theory, each waveguide of the directional coupler has a propagation constant, denoted as β_1 and β_2, respectively. For example, the normalized power of port 2 of the coupler is shown below,

$$a_2(z) = -j\kappa_{21}/s \times a_1(0)\mathrm{e}^{-j\overline{\beta}z} \sin sz, \tag{1}$$

where $a_2(z)$, $a_1(0)$ are the normalized amplitude of port 2 at z, the normalized amplitude in the input of port 1, respectively; κ_{21} is the coupling coefficient, s represents the degree of coupling and difference of β_1 and β_2, $\overline{\beta}$ equals the average of β_1 and β_2. Assuming that light launches into port 2, the optical power can be coupled to port 2 completely at the beat length when β_1 equals β_2. A smaller difference between β_1 and β_2, and a larger power can be obtained at port 2 at the beat length.

In the case of PD, it is preferred that more light is in the ML before coupling into the absorber. In order to maximize the coupling efficiency, the effective refractive index of the ML can be adjusted to be close to the fundamental mode refractive index of the DW by changing the thickness of material. As illustrated in Fig. 1, we chose two layers for the ML: 1.1Q and 1.3Q. 1.1Q is the same material as employed in the DW and placed on the top of DW, while 1.3Q with larger refractive

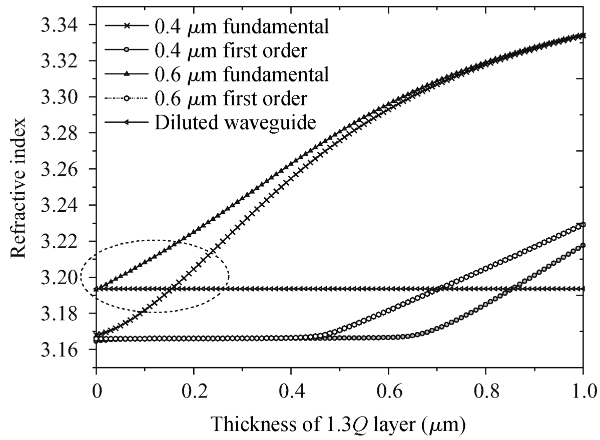

Fig. 2. Calculated refractive index of the ML and the DW with different thicknesses of 1.3Q layer when the thicknesses of the 1.1Q layer beneath the 1.3Q layer are 0.4 μm and 0.6 μm, respectively.

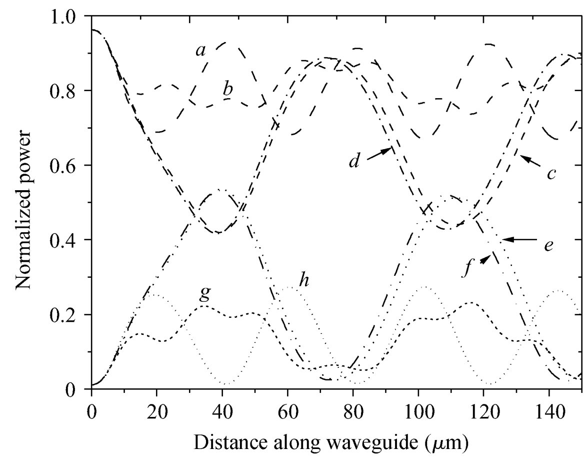

Fig. 3. Normalized power profile in DW (a, b, c, d) and ML (e, f, g, h) with different thicknesses of them. (a) 1.1Q: 0.4 μm, 1.34Q: 0.3 μm. (b) 1.1Q: 0.6 μm, 1.3Q: 0.5 μm. (c) 1.14Q: 0.6 μm. (d) 1.1Q: 0.4 μm, 1.3Q: 0.16 μm. (e) 1.1Q: 0.6 μm. (f) 1.1Q: 0.4 μm, 1.3Q: 0.16 μm. (g) 1.1Q: 0.6 μm, 1.3 Q: 0.5 μm. (h) 1.1Q: 0.4 μm, 1.3Q: 0.3 μm.

index is needed for adjusting the whole ML index. Although other materials with a larger refractive index, such as 1.4Q, are more efficient for optical coupling they may be opaque to the operating wavelength, deteriorating the absorption efficiency. As shown in Fig. 2, the fundamental and first-order modes of the ML and the DW are calculated separately with different thicknesses of 1.3Q layer and 1.1Q layer. These two waveguides are both single mode operations when the thickness of the 1.3Q layer is less than 0.5 μm. When the passive waveguide is composed of 0.6 μm or 0.4 μm thick 1.1Q layer and 0.16 μm thick 1.3Q layer, as shown in the dotted line circle in Fig. 2, for example, the effective refractive indexes of the ML and the DW are nearly the same. Then the maximum coupling efficiency can be expected.

In Fig. 3, normalized powers in the DW and the ML with different thicknesses of matching layers have been calculated by 3D-BPM, respectively, considering different thickness of matching layer. It is noted that a ML composed of one or two

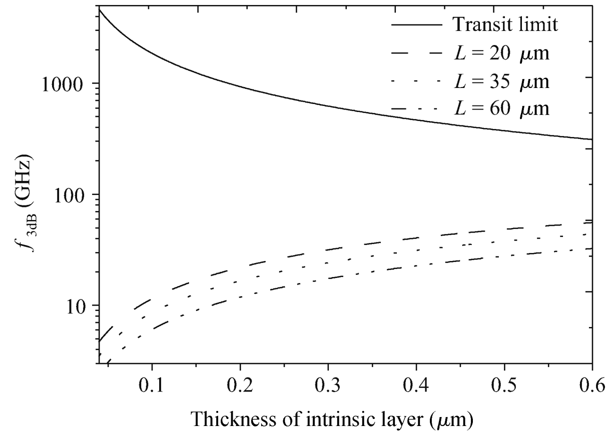

Fig. 4. Simulation of 3-dB bandwidth with different thicknesses and lengths of absorber.

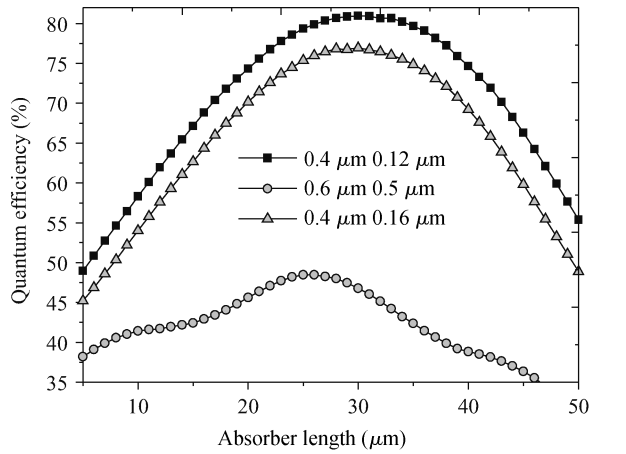

Fig. 5. Simulation of quantum efficiency of an absorber with different lengths and ML structure.

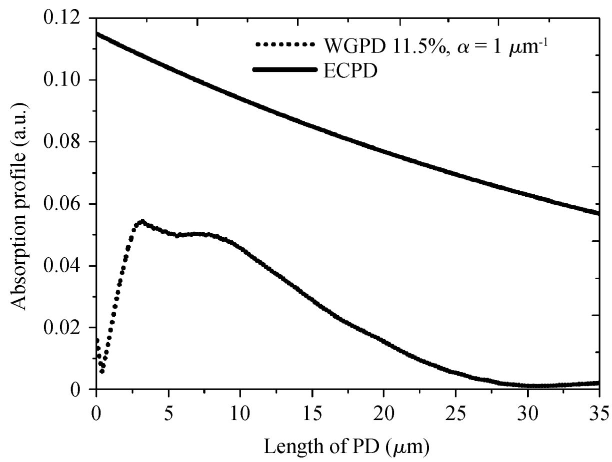

Fig. 6. Simulation of the absorption profile of our structure and the conventional waveguide photodiode.

InGaAsP layers can obtain the maximum coupling efficiency, as shown in Fig. 4. Since the refractive index is larger in the absorber, the $1.3Q$ layer can help light to be coupled into the absorber efficiently with a thinner layer. Therefore, the structure with two InGaAsP layers is more preferable and seems to be the most promising candidate for EC-WPDs compared to those in the previous work[3, 4]. The design of the ML length (denoted as L in Fig. 1) will be depicted in the next section considering the absorbing efficiency of absorber.

2.3. Absorber

The material of absorber is $In_{0.53}Ga_{0.47}As$ for detecting the 1.55 μm light. The thickness can be chosen by estimating the bandwidth for high speed operation and absorption efficiency. The bandwidth of PDs is limited by the carrier transport time ($1/f_t$) and the resistance–capacitance (RC) time ($1/f_{RC}$) constant, and the net O–E bandwidth can be approximated as follows[8]:

$$1/f_{3dB}^2 \cong 1/f_t^2 + 1/f_{RC}^2. \qquad (2)$$

The transit time bandwidth can be calculated by $f_{tr} \approx \frac{3.5\overline{v_{tr}}}{d}$, where $\overline{v_{tr}}$ is the average velocity (6.5×10^6 cm/s) of electrons and holes. The RC bandwidth can be obtained by $f_{RC} = 1/2\pi C(R_s + R_L)$ employing the parameters in Ref. [9], where C, R_s, R_L are the diode capacitance, the series resistance and the load resistance, respectively. Finally, the 3-dB bandwidth of a PIN PD (5 μm width) with different absorber thicknesses W and diode lengths is shown in Fig. 4, suggesting that PDs with the 35 μm length and 0.5 μm absorber thickness allow simultaneously a bandwidth of approximate 40 GHz and a high responsivity. The bandwidth of PDs with this structure is primarily limited by the RC. Exact values of the components can be extracted by S parameter measurement[10] and then more accurate results can be obtained.

After obtaining the thickness and length of the absorber, the length of the ML can be determined by taking the optical coupling between these two layers into account. From the view of the approach presented in the former section, the variation of optical power in the passive waveguide can be regarded as a consequence of the beat effect between the fundamental and first-order modes of the passive waveguide. It is noticeable that these two modes are different from the fundamental mode mentioned above. They can be treated as a result of perturbation and interference between the fundamental modes of the ML and the DW. Optical intensity is at a maximum in the ML when L equals the beat length (about 40 μm in Fig. 3, $L\pi$). In practice, L should be shorter than $L\pi$ due to a limited effective length of the absorber caused by the beat effect existing between absorber and ML. Hence if L is shorter (30 μm is the optimal value in Fig. 5), PDs will have a higher quantum efficiency and much more uniform light absorption, as shown in Fig. 6. It is worth noting that the ML in the simulation is a little different, consisting of 0.4 μm $1.1Q$ and 0.12 μm $1.3Q$ that are also in the dotted line circle of Fig. 3 for higher absorbing efficiency. The small difference may be caused by interference among the absorber, the ML and the DW, which is more complex than our simplified model. An absorber with length longer than 35 μm is not helpful for high responsivity and high bandwidth due to a larger RC limit. As shown in Fig. 5, the external efficiency is as high as 81% utilizing the optimal structure. While using other structures in Fig. 3, for example, 0.4 μm, $1.3Q$: 0.16 μm obtains 76% and 0.6 μm, $1.3Q$: 0.5 μm 47%. All of the above results can be obtained quickly by 3D-BPM after determining the materials and thicknesses of the ML.

In addition, the ability to handle high power is also improved in EC-WPDs compared to that in conventional waveguide photodiodes. The optical intensity in the conventional waveguide PD is calculated as

$$P = P_0[1 - \mathrm{e}^{-\Gamma(z)\alpha z}], \tag{3}$$

where P_0 is the intensity at the start of the absorber section, $\Gamma(z)$ is the optical confinement factor, α is the absorption coefficient in the absorber and z is the distance measured from the front end. The power in EC-PDs is simulated by the 3D-BPM. The absorption profile along the absorber, which affects the saturation behavior of the waveguide photodiode, is obtained by taking the spatial derivative of the total optical intensity. More uniform light absorption can be realized in the EC-PDs, as depicted in Fig. 6. Therefore, better linearity and a higher saturation current can be expected for EC-PDs.

3. Conclusion

High efficiency (81%), nearly 40 GHz bandwidth and high linearity EC-WPDs have been designed by the CMT and the BPM. Although the optimization process of different parts of the PD in the paper is separate, the optimum structure of the whole device can be obtained without any additional calculation.

Although the PDs designed here operate at a wavelength of 1.55 μm with a PIN structure, the method presented here is also applicable to devices working at another wavelength or utilizing other structures, such as a uni-traveling carrier photodiode[11]. The simulation results show that EC-WPDs are promising devices for future optical communication systems.

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