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Optical matching layer structures in evanescent coupling photodiodes at a wavelength of 1.55 μm: physics, design and simulation*

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We have studied the optical matching layers (OMLs) and external quantum efficiency in the evanescent coupling photodiodes (ECPDs) integrating a diluted waveguide as a fibre-to-waveguide coupler, by using the semi-vectorial beam propagation method (BPM). The physical basis of OML has been identified, thereby a general designing rule of OML is developed in such a kind of photodiode. In addition, the external quantum efficiency and the polarization sensitivity versus the absorption and coupling length are analysed. With an optical matching layer, the absorption medium with a length of 30 μm could absorb 90% of the incident light at 1.55 μm wavelength, thus the total absorption increases more than 7 times over that of the photodiode without any optical matching layer.

Keywords: optical matching, evanescent coupling, diluted waveguide, waveguide photodiode
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1. Introduction

Compared with the direct optical absorption of waveguide photodiodes, evanescent coupling offers a uniform distribution of photo-generated carriers around the active area and, thus, a better linearity and a higher saturation optical power can be obtained.[1] Moreover, the integrated waveguide allows the optimization of fibre-to-chip coupling and does not affect the photodiode electrical performance.[2] And this kind of photodiode only needs a single crystal layer epitaxially grown on an unmasked InP wafer, so it is relatively easy to fabricate. Unfortunately, this kind of photodiode needs a large active area to absorb the incident light completely due to its special absorption way.[3,4] This results in high capacitance and thus a low bandwidth. In order to improve the bandwidth and reduce the junction capacitance, various methods of enhancing the evanescent coupling, such as grating coupling,[5] butt coupling[6] or ARROW-type coupling,[7] have been proposed, and all of these methods are artful but more complex in fabrication.

Thus, the optical matching, which is also called impedance matching, has been proposed and adopted for realizing the evanescent coupling enhancement and an enhancement factor of 700% has been gained.[8] Photodiode with a responsivity as high as 1.02 A/W and a bandwidth up to 48 GHz has been demonstrated, which is composed of a diluted waveguide and an optical matching layer (OML).[9] Recently, a series of the state-of-the-art performances of photodiodes integrating a diluted waveguide and an OML has been fabricated.[9−14] Usually, the structure of this kind of photodiode is designed and optimized by a genetic algorithm (GA),[10,11,14] coupling with the BPM.[15,16] This involves a great many of parameters in a large range. Although the photodiodes can be optimized precisely in this way, it is largely time-consuming. Half a month or more is taken to complete the optimization. Instead of the GA optimization method, a general designing rule of OML has been developed.

The scheme of the epitaxial structure is shown in Fig.1. An optical matching layer is just on the top of the diluted waveguide, which is designed as a fibre-to-waveguide coupler,[17] to achieve a high coupling efficiency and low polarization sensitivity or, quasi-independence. The rest of the present paper is organized as follows. In Section 2, the external quan-

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tum efficiency and evanescent coupling with different optical matching layers are calculated by using the semi-vectorial BPM (see Refs.[15–17] for more details). Also, in Section 2, the numerical results are analysed and compared with the theory and the mechanism proposed by Deri and Wada[8] and Hawkins *et al*[18] and the physical basis of OML in evanescently coupled photodiode (ECPD) is identified. In Section 3, a general designing rule of OML is developed, thereby the optimization epitaxial structure of OML is presented. The performance of the ECPD is investigated and discussed in detail.

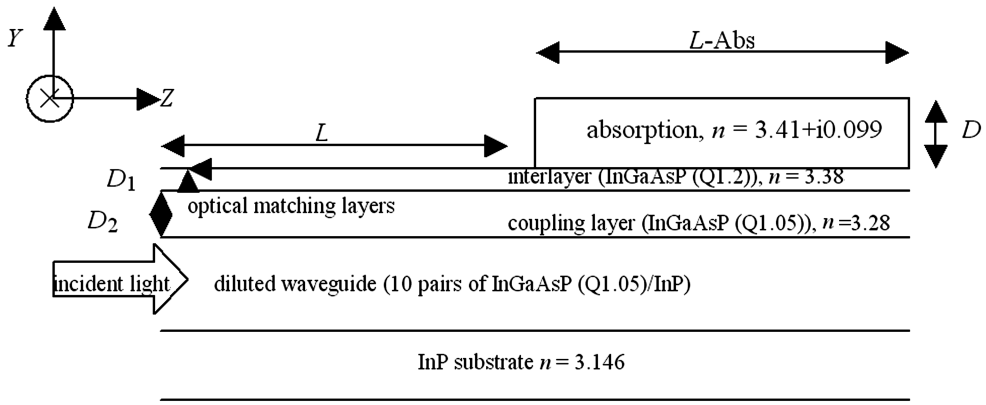


Fig.1. Side cross section of the evanescently coupled photodiode integrating a diluted waveguide as a fibre-to-waveguide coupler. All of the parameters in the scheme are indicated in the text.

2. Physical considerations and simulation

As designed in Ref.[17], the diluted waveguide is composed of ten periods of un-doped 120-nm /80-nm InP/InGaAsP (1.05-μm bandgap). The fundamental mode distribution and the refractive index distribution are presented in Fig.2. The central part of the mode distribution is slightly close to the refractive index of InP substrate, due to a large difference in refractive index between the surfaces of waveguide and air. Thus, a large absorption length ($> 200\,\mu$m) is needed to absorb the incident light completely as shown in Fig.3, when there exists no OML. On the contrary, we could obtain a high external quantum efficiency with quite a small absorption length ($30\,\mu$m) when the OML is adopted, which is shown in Fig.6. The light in the diluted waveguide and the light in the OML are coupled with each other strongly. The optical power distributions in the diluted waveguide and in the OML are shown in Figs.4 and 5. Figure 4 shows the optical power coupling between the diluted waveguide and the OML with the thickness $D_2 = 0.42\,\mu$m. The period is around $72\,\mu$m, and about 50% of the optical power is transferred into the coupling layer through half a period. Figure 6 shows the optical power in the OML

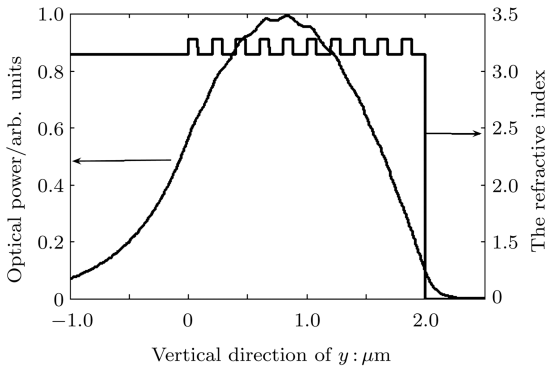


Fig.2. Distribution of TE fundamental mode field in the diluted waveguide with ten periods of 120 nm/ 80nm InGaAsP/InP and the refractive index distribution.

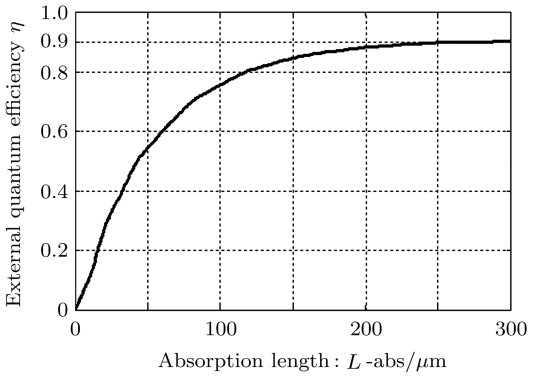


Fig.3. External quantum efficiency versus absorption length without OML, where an absorption length of over $220\,\mu$m is needed to absorb 90% of the incident light.

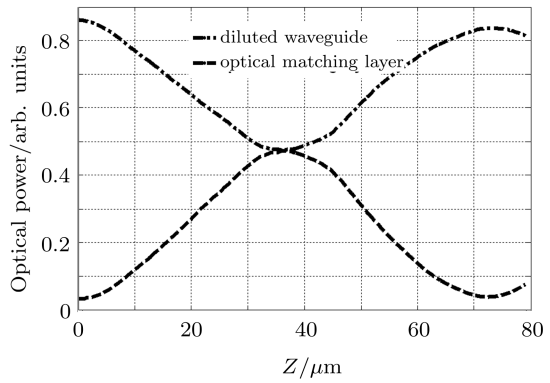


Fig.4. Optical powers in the diluted waveguide and in the coupling layer versus coupling length L ($D_2 = 0.42\,\mu$m, $D_1 = 0.1\,\mu$m).

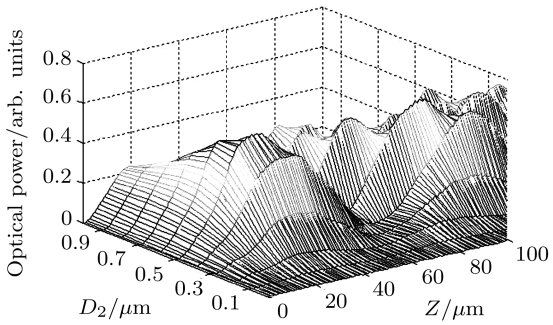


Fig.5. Optical power in the OML versus thickness of D_2 along the z-direction, showing that the power in the OML is quite low when $D_2 < 0.3\,\mu$m, but it arrives at a maximum at a thickness of about $0.5\,\mu$m.

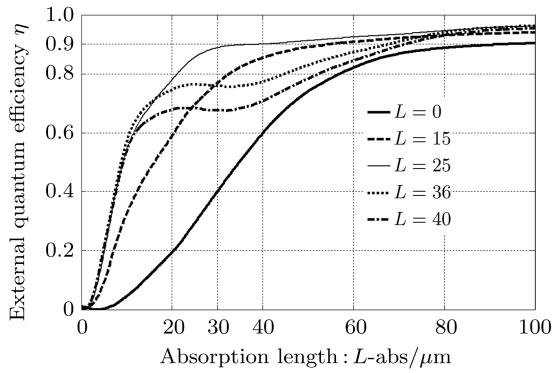


Fig.6. Curves for external quantum efficiency versus the L-abs at different values of L ($D_1 = 0.1\,\mu$m, $D_2 = 0.42\,\mu$m), with a diluted waveguide width being $4\,\mu$m.

varies with D_2 and the power distribution along the z-direction. A coupling efficiency up to 60% is obtained when D_2 is around $0.5\,\mu$m. When the OML is employed, an additional mode is introduced into the OML, which is coupled with the modes in the diluted waveguide and affects the external quantum efficiency strongly. Thus, the external quantum efficiency is quite sensitive to the coupling length L. And the curve for the external quantum efficiency versus the coupling length L oscillates violently, following a sinusoidal curve with period varying with D_1 value as shown in Fig.7.

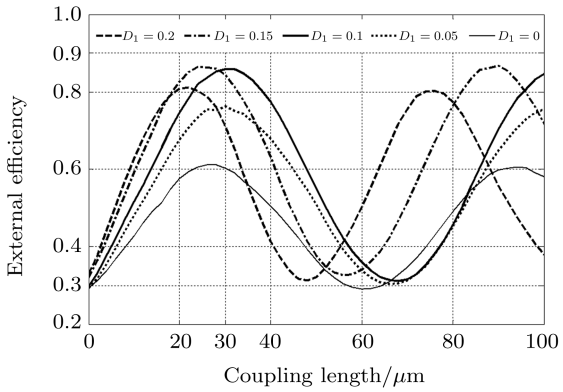


Fig.7. External quantum efficiencies versus coupling length, where each curve represents a different value of D_1($D_2 = 0.42\,\mu$m, L-abs $= 20\,\mu$m) and the peak value of η, higher than 85%, appears between D_1 values of 0.1 and $0.15\,\mu$m.

Compared with Fig.4, Fig.6 obviously shows that the external quantum efficiency increases with coupling length L increasing as long as the absorption length is less than $17.5\,\mu$m, when L is less than half the coupling period, $36\,\mu$m, as presented in Fig.4. Increasing the absorption length L, the external quantum efficiency degrades to some extent as it approaches the maximum point of the curve in Fig.4. This is due to the beating between the modes in the diluted waveguide and the coupling layer, and also this beating takes place between the modes in the coupling layer and the absorption layer. As $L < 36\,\mu$m, the power is transferring from the diluted waveguide to the coupling layer, and at the same time, the power is leaked into the absorption layer from the coupling layer. This is just in the opposite direction when $L > 36\,\mu$m, therefore, the external quantum efficiency reduces. The function of coupling layer is just to let the central part of the mode distribution which is slightly close to the InP substrate, as shown in Fig.2, be at the centre of the diluted waveguide, or even close to the waveguide's upper side to make the light power leak into the absorption layer more easily through the evanescent coupling. This is some kind of the 'two-step coupling mechanism', proposed by Hawkins.[18] In order

to realize the function, and considering the epitaxial structure of the diluted waveguide, InGaAsP with the same composition as that in the diluted waveguide is adopted as the coupling layer in the OML, and the low refractive index between the coupling layer and diluted waveguide is obtained, also the low reflectivity in the interlayer and thus, the coupling between them is enhanced.

As dedicated in Fig.7, the maximum external quantum efficiency η with adopting an interlayer is much higher than that without adopting any interlayer ($D_1 = 0$). A comparison of maximum η between the cases where $D_1 = 0$ and $D_1 = 0.15\,\mu$m shows a difference of about 30%. Figure 4 shows the maximum external quantum efficiency varying with the thickness of interlayer in the OML. This indicates that the adopting of interlayer could effectively increase the external quantum efficiency. And the shape of this curve looks like that of an antireflection layer, which has been proposed by Deri and Wada.[8] Unfortunately, he soon afterward denied this model in Ref.[18]. Though the coupling layer is adopted, there remains a large difference in refractive index between the absorption layer and the coupling layer. The interlayer could further reduce the difference in index effectively, and then reduce the reflectivity at the interface between the coupling layer and the absorption layer. Therefore, the interlayer in the OML as an antireflection layer could increase the external quantum efficiency greatly.

3. Design and discussion

According to the physical basis identified above, the materials of coupling layer and interlayer in OML are almost fixed and so there is no need to optimize the refractive indices of OML with the GA method in a large range. The coupling layer is of the quaternary material the same as that in the diluted waveguide, while the interlayer may be of any one of the quaternary materials, whose refractive index must be between those of the coupling layer and absorption layer. The coupling and the antireflection of OML in ECPD with diluted waveguide are basic functions and, thus, the coupling layer and the interlayer are general in all OMLs in ECPD with diluted waveguide, and so is the rule for choosing coupling layer and interlayer. This has been demonstrated in the ECPDs integrating diluted waveguides.[9,14]

And now, the only thing we need to do is just to optimize the thicknesses of coupling layer D_2 and interlayer D_1. and then the coupling length L and the corresponding absorption length L-abs. Using the BPM, we calculated the optical coupling efficiencies between the diluted waveguide and the coupling layer with different values of D_2, and the results are presented in Fig.5. Choosing $D_2 = 0.42\,\mu$m, we calculate the maximum external quantum efficiencies varying with D_1, the calculations are shown in Fig.8. The highest external quantum efficiency is obtained when D_1 is about $0.1\,\mu$m. Noting those curves presented in Fig.6, the optimal working point for a photodiode should be at the 'shoulder', around 30 and $25\,\mu$m for the absorption and the coupling lengths, respectively. A comparison of external quantum efficiency between without OML and with OML, shown respectively in Fig.3 and Fig.6, indicates that the external quantum efficiency is enhanced to over 700%, which arrives at the level the same as that given in Ref.[8].

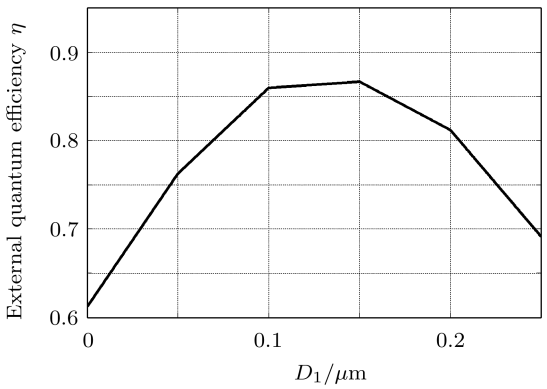


Fig.8. The maximum external quantum efficiency versus thickness of interlayer D_1. ($D_2 = 0.42\,\mu$m)

The dependences of external quantum efficiency on absorption length with different diluted waveguide widths and polarization modes have also been investigated as shown in Fig.9. The dependences of external quantum efficiency on absorption length when the diluted waveguide width is $4\,\mu$m and $10\,\mu$m are almost the same. The external quantum efficiency is not sensitive to width. The diluted waveguide with a width of $10\,\mu$m has higher order modes, which just exist in the x-direction, and in the y-direction the waveguide is so thin that there exists only a fundamental mode (see Ref.[17], in which the modes of the diluted waveguide are studied in detail). The optical power coupling is in the y-direction, and the higher order modes in the x-direction, induced by a larger width, have little in-

fluence on it. The electromagnetic field compositions of TE and TM modes are (E_x, H_y, H_z) and (H_z, E_y, E_z), respectively. Therefore, this kind of photodiode is polarization dependent. Fortunately, due to the adoption of the diluted waveguide as a fibre-to-waveguide coupler, The polarization sensitivity is less than 0.8-dB at the optical matching layer $L = 25\,\mu$m, as shown in Fig.9.

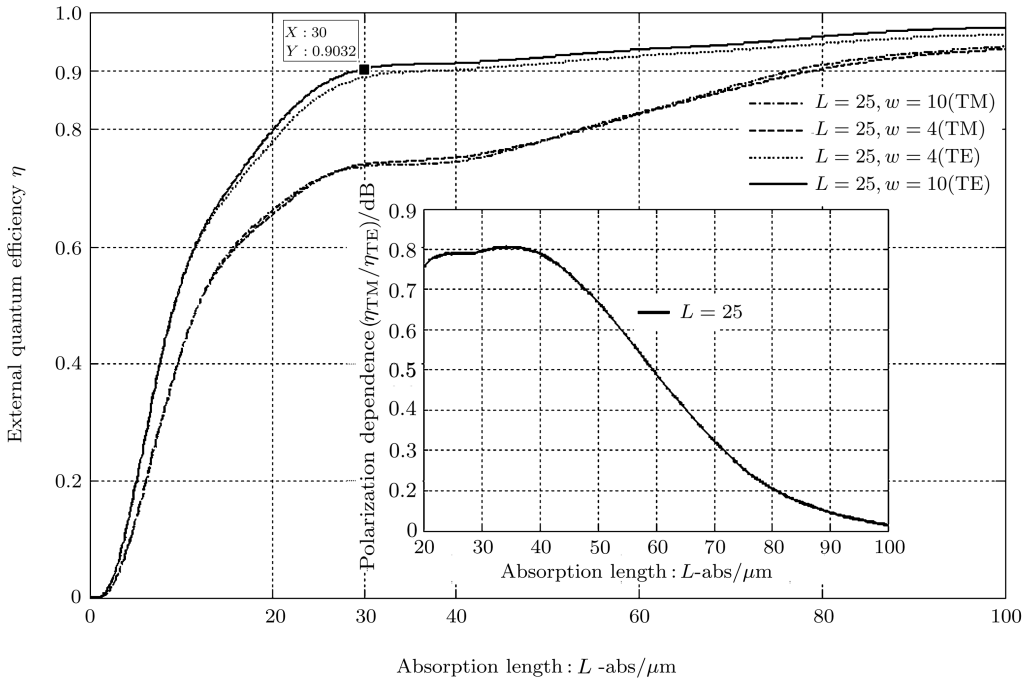


Fig.9. External quantum efficiency versus absorption length with different values of diluted waveguide width w and different polarization modes, where the inset shows polarization sensitivity ($\eta_{\rm TM}/\eta_{\rm TE}$) versus absorption length and the polarization sensitivity is less than 0.8dB at the optical matching layer $L = 25\,\mu$m.

4. Conclusion

Using the semi-vectorial BPM algorithm, we have calculated the optical power transferring between the coupling layer and the diluted waveguide and investigated the external quantum efficiency versus the absorption and coupling length. The calculation results are analysed carefully, and then the physical basis of the OML in the diluted waveguide is identified. A comparison between the OML working mechanisms proposed by Hawkins[18] and Deri and Wada,[8] separately indicates that they are quite consistent with each other. According to this, a general rule for designing the OML in ECPD with diluted waveguide is developed, which can simplify the optimization of OML effectively. Applying these results to the OML design, the external quantum efficiency is enhanced up to 90%, with the absorption length being just $30\,\mu$m. The absorption that is enhanced up to 700% of that for the photodiode without adopting any OML is demonstrated theoretically, which has arrived at the level the same as the results published in Refs.[8, 9].

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