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Characteristic analysis of the optical delay in frequency response of resonant cavity enhanced (RCE) photodetectors*

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With consideration of the modulation frequency of the input lightwave itself, we present a new model to calculate the quantum efficiency of RCE p-i-n photodetectors (PD) by superimposition of multiple reflected lightwaves. For the first time, the optical delay, another important factor limiting the electrical bandwidth of RCE p-i-n PD excluding the transit time of the carriers and RC_d response of the photodetector, is analyzed and discussed in detail. The optical delay dominates the bandwidth of RCE p-i-n PD when its active layer is thinner than several 10 nm. These three limiting factors must be considered exactly for design of ultra-high-speed RCE p-i-n PD.

Keywords: electrical bandwidth, frequency response, optical delay, photodetectors
PACC: 2940P, 4225B, 0660J

1. Introduction

The photodetector is an indispensable component in modern optical communication systems, and it is used to convert the optical signal into an electrical signal, which will be amplified and processed by the following receiver electronic circuits. The p-i-n photodiode has high-speed performance for high-bit-rate optical communication systems. There are two important characteristics of the high-performance photodetector, i.e. its external quantum efficiency and its electrical bandwidth. It is well known that the electrical bandwidth can be increased efficiently by reducing the intrinsic region length. But the external quantum efficiency will decrease with decreasing the thickness of the active layer. The tradeoff between its quantum efficiency and electrical bandwidth of conventional p-i-n photodetectors can be achieved by using the RCE p-i-n PD. A schematic structure of the RCE p-i-n PD is shown in Fig.1. In this structure, a thin absorbing layer is put inside Fabry–Pérot cavity.[1,2] The Fabry-Pérot cavity has two parallel mirrors, which are comprised of quarter wavelength stacks. So the light at the resonant condition will be reflected several times in the cavity by the mirrors, and the quantum efficiency at the wavelength of interest can be close to unity under proper design.

Ünlü[3] derived the most classic expressions of the electric field in the cavity and the quantum efficiency by the self-consistent method. Tung *et al* [4] calculated the frequency response of the RCE photodetector with consideration of a sine square function of the field distribution in i-region. Based on a more exact calculation of the light intensity distribution in different regions of the photodetector, a frequency analysis of the RCE photodetector was presented by Jervase in Ref.[5]. In Ref.[6], a time response for a heterostructure p-i-n photodetector was presented. El-Batawy [7] presented a detailed analysis, optimization and SPICE modeling of the RCE p-i-n photodetector. All the models mentioned above just considered the two factors limiting the speed of the photodetector, the transit time and the RC_d time constant, where R is the photodetector's equivalent resistant and C_d is its capacitance. Both the factors are caused by the electrical signal after the photons are absorbed by the active region and converted to the photo-generated carriers.

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In practice, the light is reflected by the mirrors several times in the cavity until it is absorbed totally by the active layer. The time of the light traveling in the cavity, which is called the optical delay in our paper, is so large that it must be considered exactly in the frequency analysis when the absorbing layer is thin enough. Surprisingly, this optical delay is left out of many papers on RCE p–i-n PD.

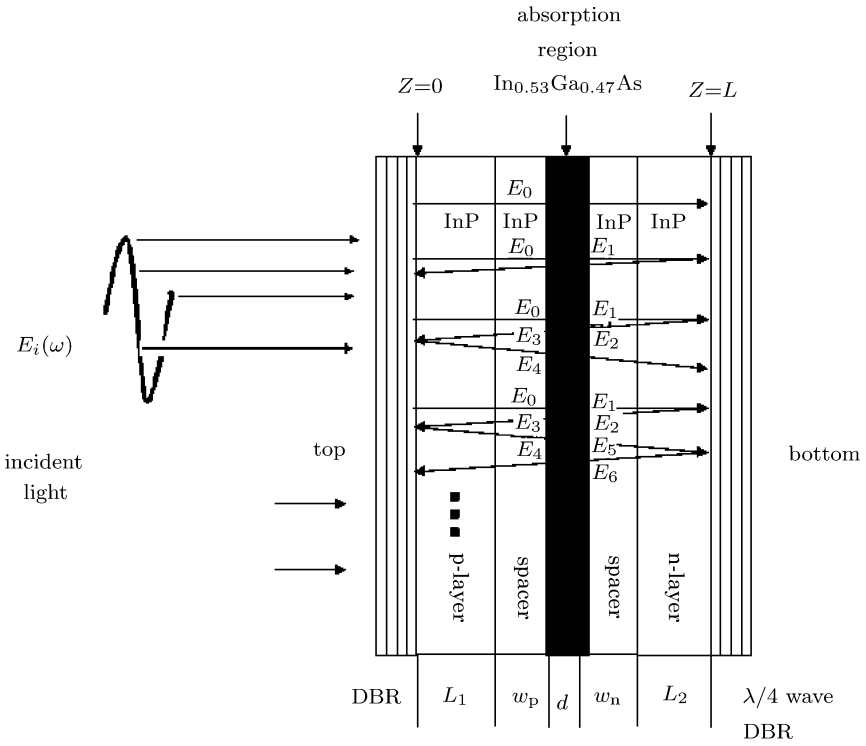


Fig.1. Schematic structure of RCE p-i-n PD. The length of the cavity L is set to be 2.5 μm. The reflectance R_2 of the bottom DBR is 0.99, and the reflectance R_1 of the top DBR is optimized according to the formula $R_1 = R_2 e^{-2\alpha_{\text{eff}} d}$.[3]

In this paper, we firstly introduce a new method to calculate the quantum efficiency of the RCE p-i-n PD. Taking into account the modulation frequency of the input lightwave, the forward electric field and backward electric field of the light at the interface between the active layer and the space layer are derived by superimposition of multiple reflected lightwaves. And then the frequency response of RCE p-i-n PD is calculated and analyzed with an assistant of El-Batawy's model.[7]

2. Physical model

2.1. The quantum efficiency of the RCE p-i-n PD calculated by superimposition

It is assumed that the input optical signal E_i is modulated by an electrical function $f(t) = e^{j\omega t}$, and it is expressed as

$$E_i = A_0 \cdot f(t), \tag{1}$$

where A_0 is the amplitude of electrical field of the input optical signal, t is time and ω is the angular frequency of the electrical function. The input lightwave transits through the top DBR mirror, the p-layer and the top space layer, and then reaches the interface between the top space layer and the active layer. Because the initial phase of the input lightwave has no impacts on the final efficiency of PD, it is assumed that the electric field of the input lightwave on the interface ($x = L_1 + w_p$) is

$$E_0(\omega) = E_i(\omega) t_1, \tag{2}$$

where t_1 is the transmission coefficient of the top DBR mirror. And then part of the optical power will be absorbed by the active layer, and the remainder will transit through the bottom space layer, the n-layer

and be reflected partly by the bottom DBR mirror. The lightwave will transit ceaselessly in the cavity just like the progress above until it is absorbed totally by the active layer. We define that the E_{4k+1}, E_{4k+4} are the electrical fields of the forward lightwave on the bottom interface and the top interface in the $k_{\rm th}$ loop, respectively, E_{4k+2}, E_{4k+3} are the electrical fields of the backward lightwave on the bottom interface and the top interface in the $k_{\rm th}$ loop, respectively. They are express as

$$E_{4k+1}(\omega) = E_0(\omega) \cdot (C_1)^{k+1} (C_2C_3C_4)^k, \quad (3)$$

$$E_{4k+2}(\omega) = E_0(\omega) \cdot (C_1C_2)^{k+1} (C_3C_4)^k, \quad (4)$$

$$E_{4k+3}(\omega) = E_0(\omega) \cdot (C_1C_2C_3)^{k+1} (C_4)^k, \quad (5)$$

$$E_{4k+4}(\omega) = E_0(\omega) \cdot (C_1C_2C_3C_4)^{k+1}, \quad (6)$$

where $k = 0, 1, 2, 3, \ldots,$

$$C_1 = \mathrm{e}^{-\mathrm{j}(\omega \Delta t_1 + k_{\rm ele} d + \beta d) - \frac{\alpha_{\rm eff} d}{2}},$$

$$\Delta t_1 = d/\upsilon, \quad (7)$$

$$C_2 = r_2 \mathrm{e}^{-\mathrm{j}[\omega \Delta t_2 + 2k_{\rm ele}(L_2 + w_n) + 2\beta(L_2 + w_n)] - \phi_2},$$

$$\Delta t_2 = 2(L_2 + w_n)/\upsilon, \quad (8)$$

$$C_3 = \mathrm{e}^{-\mathrm{j}(\omega \Delta t_3 + k_{\rm ele} d + \beta d) - \frac{\alpha_{\rm eff} d}{2}},$$

$$\Delta t_3 = d/\upsilon, \quad (9)$$

$$C_4 = r_1 \mathrm{e}^{-\mathrm{j}[\omega \Delta t_4 + 2k_{\rm ele}(L_1 + w_{\rm p}) + 2\beta(L_1 + w_{\rm p})] - \phi_1},$$

$$\Delta t_4 = 2(L_1 + w_{\rm p})/\upsilon, \quad (10)$$

υ is the velocity of the lightwave in the cavity, $\alpha_{\rm eff}$ is the effective absorption coefficient with the consideration of the standing wave effect,[3,7] $k_{\rm ele}$ is the electrical propagation constant, β is the optical propagation constant, Δt_1, Δt_2, Δt_3, Δt_4 are the propagation times in each optical distances, d, L_1, L_2, $w_{\rm p}$, $w_{\rm n}$ are the thicknesses of the active layer, p-layer, n-layer, the top space layer, the bottom space layer, respectively, ϕ_1, ϕ_2 are the phases shifts of the top DBR and the bottom DBR, r_1, r_2 are the reflection coefficients of the top DBR and the bottom DBR, respectively.

The electrical field of the lightwave in the cavity can be divided into two parts, the forward wave and the backward wave. The forward wave in the top interface is made up of all the forward waves at that interface,

$$E_{\rm f}(\omega) = \sum_{n=4k}^{m} E_n(\omega). \quad (11)$$

The backward wave in the bottom interface can be also expressed as

$$E_{\rm b}(\omega) = \sum_{n=4k+2}^{m} E_n(\omega), \quad (12)$$

where m is the number of the loop of the lightwave transiting in the cavity. It is assumed that the power of the lightwave is absorbed totally after m loops when the electrical field of the lightwave falls down to about 1% of the $|E_0|$. So the m is defined by

$$m = 2\ln 10/(\alpha_{\rm eff} d). \quad (13)$$

The forward quantum efficiency $\eta_{\rm f}$ is a ratio between the forward optical power to the incident power,

$$\eta_{\rm f} = \eta_{\rm f}^* \left(1 - \mathrm{e}^{-\alpha_{\rm eff} d}\right) \quad (14)$$

where

$$\eta_{\rm f}^* = \frac{|E_{\rm f}(\omega)|^2}{|E_{\rm i}|^2}.$$

Similarly, the backward quantum efficiency $\eta_{\rm b}$ is

$$\eta_b = \eta_{\rm b}^* \left(1 - \mathrm{e}^{-\alpha_{\rm eff} d}\right), \quad (15)$$

where

$$\eta_{\rm b}^* = \frac{|E_{\rm b}(\omega)|^2}{|E_i|^2}.$$

Then the total quantum efficiency η of the RCE p-i-n PD is

$$\eta = \eta_{\rm f} + \eta_{\rm b}. \quad (16)$$

When the input lightwave is the direct current signal, it is obvious that the optical delay effect does not exist in the RCE p-i-n PD. The external quantum efficiency calculated by the superimposition method should be the same as the result of the self-consistent method,[3] as shown in Fig.2.

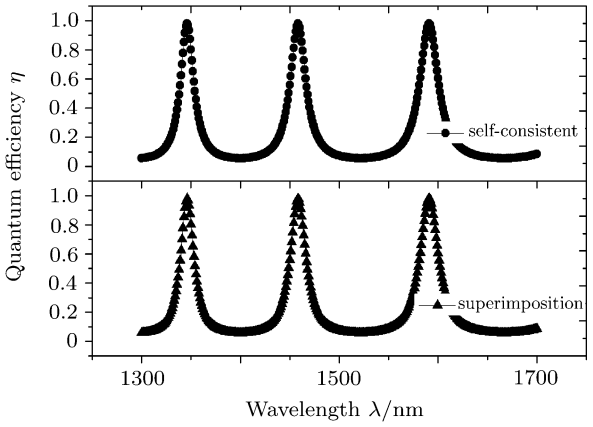


Fig.2. The absorption spectrum calculated by the self-consistent method and the superimposition method of our model, respectively.

The absorption spectra of four lightwaves with different frequencies calculated by the superimposition method are shown in Fig.3, and the absorption spectrum calculated by the self-consistent method[3] is also

shown together in Fig.3 for comparisons. From Fig.3, we can see that the absorption spectrum at the low frequency signal (1 MHz) is in very good accord with that calculated by the self-consistent method. But with increasing the frequency of the optical signal, the peak of the absorption spectrum is red-shift. The external quantum efficiency of the lightwave 1458.4 nm, which is the central wavelength of the spectrum calculated by the self-consistent method, falls down from 0.7954 to 0.2709 at 100 GHz. The cause of the red shifts is that the modulation frequency affects the phase in formula (7) to (10) and simultaneously changes the resonant central wavelength which is determined uniquely by the optical propagation constant β. Therefore, the modulation frequency of the lightwave itself is also a very important factor affecting the external quantum efficiency in high frequency RCE p-i-n PD.

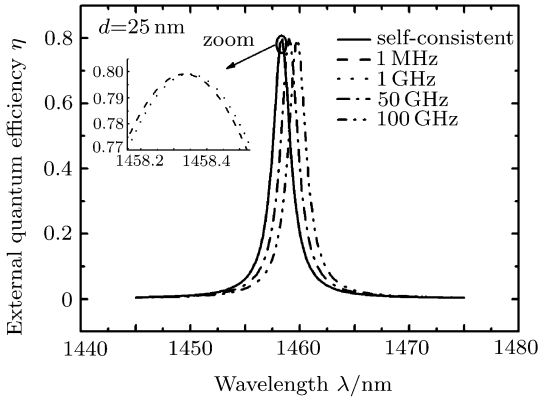


Fig.3. The absorption spectra of the four lightwaves with different frequencies calculated by the superimposition method and compared with the absorption spectrum calculated by the self-consistent method. Because the spectra of 1 MHz and 1 GHz are almost the same as that of the self-consistent method, they are separately shown in detail around the central wavelength.

2.2. Frequency response of the RCE p-i-n PD

To calculate the time response of the RCE p-i-n PD, the time response of the carriers generated due to both forward and backward lightwaves is calculated.[7] El-Batawy[7] has derived the Fourier transform of its time response to get the frequency of the RCE p-i-n PD. The Fourier representation of the photogenerated carriers is given by

$$
\begin{aligned}
N_{\rm ph}(\omega)=\frac{P_i}{h\nu}\Bigg\{&(\eta_{\rm f}^*+\eta_{\rm b}^*)\left[1-\exp(-\alpha_{\rm eff}d)\right]\cdot\left[\frac{1-\exp\left(\dfrac{-{\rm j}\omega w_{\rm n}}{\upsilon_{\rm n}}\right)}{{\rm j}\omega}\right]\\
&+\left[\eta_{\rm f}^*-\eta_{\rm b}^*\exp(-\alpha_{\rm eff}d)\right]\cdot\left[\frac{\left(1-\exp\left(\dfrac{-{\rm j}\omega d}{\upsilon_{\rm n}}\right)\right)\exp\left(\dfrac{-{\rm j}\omega w_{\rm n}}{\upsilon_{\rm n}}\right)}{{\rm j}\omega}\right]\\
&+\exp\left(\frac{-{\rm j}\omega w_{\rm n}}{\upsilon_{\rm n}}\right)\left(\eta_{\rm f}^*\left(\frac{\exp(-\alpha_{\rm eff}d)-\exp\left(\dfrac{-{\rm j}\omega d}{\upsilon_{\rm n}}\right)}{\alpha_{\rm eff}\upsilon_{\rm n}-{\rm j}\omega}\right)+\eta_{\rm b}^*\left(\frac{1-\exp\left(-\alpha_{\rm eff}d-\dfrac{{\rm j}\omega d}{\upsilon_{\rm n}}\right)}{\alpha_{\rm eff}\upsilon_{\rm n}+{\rm j}\omega}\right)\right)\Bigg\},
\end{aligned}
\tag{17}
$$

$$
\begin{aligned}
P_{\rm ph}(\omega)=\frac{P_i}{h\nu}\Bigg\{&(\eta_{\rm f}^*+\eta_{\rm b}^*)\left[1-\exp(-\alpha_{\rm eff}d)\right]\cdot\left[\frac{1-\exp\left(\dfrac{-{\rm j}\omega w_{\rm p}}{\upsilon_{\rm p}}\right)}{{\rm j}\omega}\right]\\
&+\left[\eta_{\rm f}^*-\eta_{\rm b}^*\exp(-\alpha_{\rm eff}d)\right]\cdot\left[\frac{\left(1-\exp\left(\dfrac{-{\rm j}\omega d}{\upsilon_{\rm p}}\right)\right)\exp\left(\dfrac{-{\rm j}\omega w_{\rm p}}{\upsilon_{\rm p}}\right)}{{\rm j}\omega}\right]\\
&+\exp\left(\frac{-{\rm j}\omega w_{\rm p}}{\upsilon_{\rm p}}\right)\left(\eta_{\rm f}^*\left(\frac{\exp(-\alpha_{\rm eff}d)-\exp\left(\dfrac{-{\rm j}\omega d}{\upsilon_{\rm p}}\right)}{\alpha_{\rm eff}\upsilon_{\rm p}-{\rm j}\omega}\right)+\eta_{\rm b}^*\left(\frac{1-\exp\left(-\alpha_{\rm eff}d-\dfrac{{\rm j}\omega d}{\upsilon_{\rm p}}\right)}{\alpha_{\rm eff}\upsilon_{\rm p}+{\rm j}\omega}\right)\right)\Bigg\}.
\end{aligned}
\tag{18}
$$

Taking into account the effects of the load and the parasitic element of the photodetectors, the extrinsic current[7] is expressed as

$$I(\omega) = \frac{q\left[\upsilon_{\mathrm{n}} N_{\mathrm{ph}}(\omega) + \upsilon_{\mathrm{p}} P_{\mathrm{ph}}(\omega)\right]}{(d + w_{\mathrm{n}} + w_{\mathrm{p}})\left(1 - \omega^2 L C_d + \mathrm{j}\omega R C_d\right)}, \quad (19)$$

where q is the elementary charge, L is the parasitic inductance of the photodetector including the wire bond inductance, $C_d = \varepsilon_o \varepsilon_r A/d$ is the total capacitance of the photodetector, R is the total resistance that includes the load resistance and the photodetectors's serial resistance. The normalized frequency response can be detemined from Eq.(19), and can be expressed as

$$F(\omega) = 20 \log_{10} \left| \frac{I(\omega)}{I(0)} \right|. \quad (20)$$

3. Results and discussion

The extrinsic bandwidth depends on three effects, not only the transit time of the carriers and the RC_d response of the photodetector, but also the optical delay in high frequency RCE photodetetor. Decreasing the thickness of the active layer to increase the intrinsic bandwidth results in an increase in the capacitance. The extrinsic bandwidth will decrease according to Eq.(20) due to the increase of the capacitance. And when the thickness of the active layer decreases to the order of 10 nm, the absorption ability in a loop is very low, and the optical delay becomes serious. In order to reduce the RC_d effect especially for small thickness of the active layer, two 300 nm-spacers are

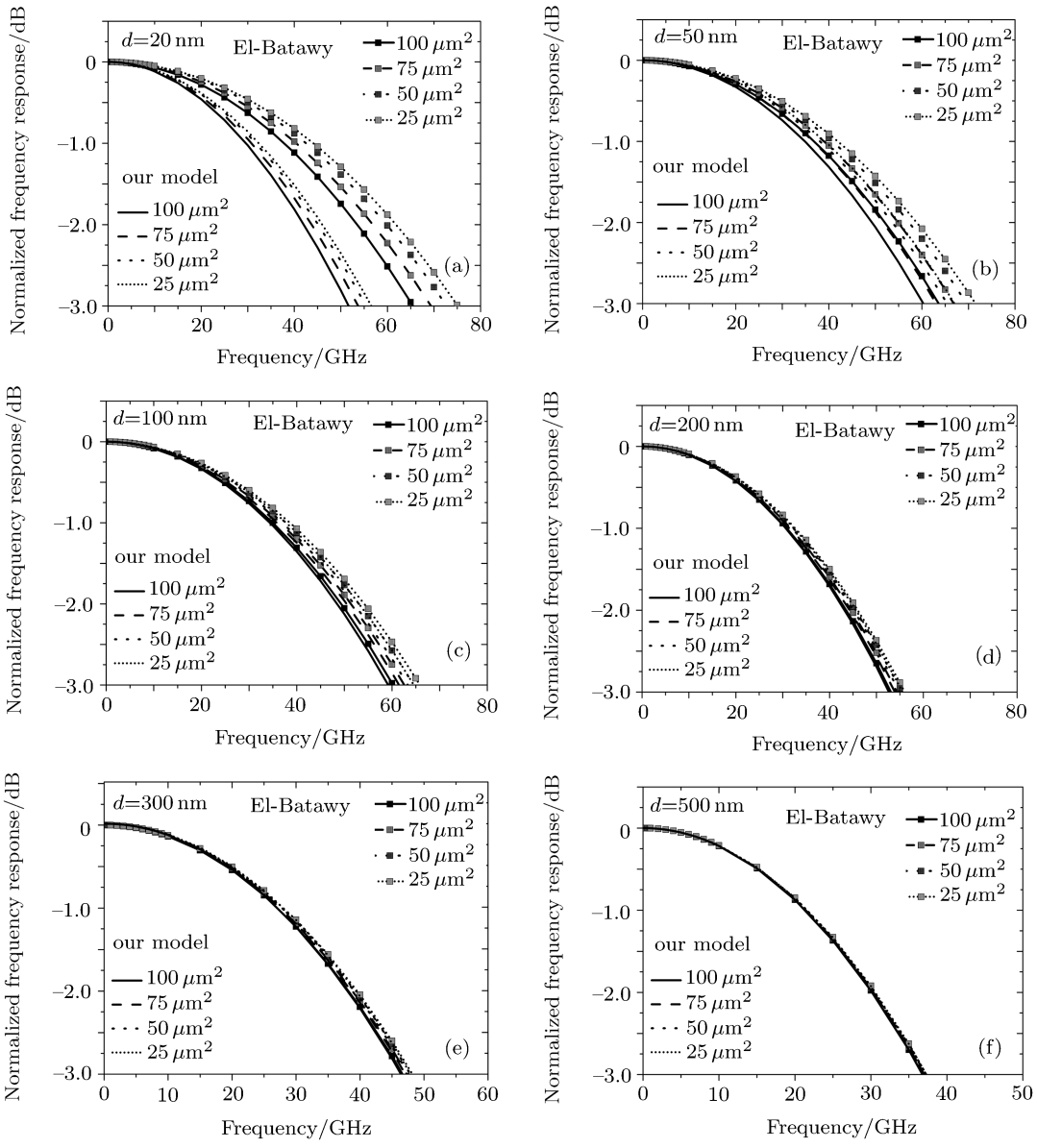


Fig.4. Normalized extrinsic frequency responses for different areas of the photodetector and for different thicknesses of the active layer: (a) 20 nm, (b) 50 nm, (c) 100 nm, (d) 200 nm, (e) 300 nm, (f) 500 nm.

inserted between the active layer and the electrode layers. The load resistor is 50 Ω and the serial resistance of the photodetector is assumed to be 5 Ω. The extrinsic bandwidths of these photodetectors with 6 different thicknesses of the active layer and 4 different areas are shown in Fig.4.

It can be seen from Fig.4 that there is a big difference between the result of the El-Batawy's model and that of our model for 20 nm thickness of the active layer. The optical delay is the major part on this situation for the high frequency RCE photodetector. With increasing the thickness of the active layer to several hundred nanometers, the difference between them becomes less. Firstly, the RC_d response limits the extrinsic bandwidth of the photodetector because of the large capacitance. With increasing the thickness of active layer to be more than 300 nm, the transit time dominates the frequency response of the photodetector. Therefore, the extrinsic bandwidth for 500 nm thickness of the active layer and different areas are almost the same, shown in Fig.4(f).

From the above discussions, we can see that the RC_d and the transmit time are the major factors limiting the electrical bandwidth in common RCE PD. But the optical delay time, which is an intrinsic factor in RCE PD, becomes serious when the absorption layer is thin enough. Therefore, the optical delay time must be considered exactly in the design of the ultra-high-speed RCE p-i-n PD.

4. Conclusion

With consideration of the modulation frequency of the input lightwave itself, we present a new model to calculate the quantum efficiency of RCE p-i-n PD by the superimposition method for multiple reflected lightwaves. For the first time, optical delay, another important factor limiting the electrical bandwidth of RCE p-i-n PD excluding the transit time of the carriers and RC_d response of the photodetector, is analyzed and discussed in detail. The optical delay dominates the bandwidth of RCE p-i-n PD when its active layer is thinner than several 10 nm. These three limiting factors must be considered exactly for design of ultra-high-speed RCE p-i-n PD.

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