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A Novel Resonant-Cavity-Enhanced (RCE) Photodetectors principle and performance

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Abstract: A new Resonant Cavity Enhanced Photodetector is introduced, including fully theoretical deducing & simulation analysis. By comparing with conventional optical Photodetector, It shows that RCE overcome the tradeoff between QE and response speed lies in conventional PD to some extent, the enhanced effect in resonant wavelengths resulting from resonant cavity enables RCE PD with inherent wavelength selectivity which is quite attractive for WDM systems.

Keywords: Resonant Cavity Enhanced Photodetector; quantum efficiency; Standing Wave Effect; WDM

INTRODUCTION

The progress in optical wavelength division multiplexing (OWDM) communication technology show the great advantages of photodetectors with wavelength selection and high response speed in optical communication. A new type of photodetector - resonant cavity enhancement (RCE) photodetector which inserts the absorption layer into resonant cavity, is proposed. The conflict between quantum efficiency and response speed of traditional detector could be solved due to the higher quantum efficiency of thinner absorption layers from the enhancement effect of the resonant cavity , less transit time of the light carrier, and the resulting higher response speed In addition, there is no auxiliary filters for photodetectors because a resonant cavity has the capability of wavelength selection [1], and they are, therefore, potential to be a new generation of photodetector in WDM optical fiber communication system.

1. Structure and quantum efficiency analysis of RCE component: Quantum efficiency is a physical quantity representing the photoelectric conversion efficiency, which is defined as:

$$\eta = (I_p / e_0)/(P_0 / hv) \tag{1}$$

Here, Lp is photoelectric current intensity, Eo is electron charge, and Po is incident light intensity. The structure principle of RCE component is shown in **Fig.** 1.

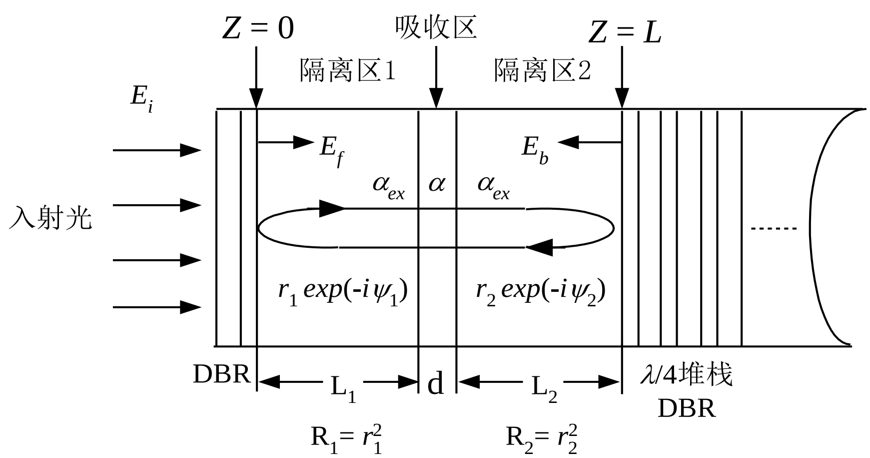


Fig.1: Structure analysis model of RCE detector

The DBR at the top and bottom is composed of alternating non-absorptive wide-band material, and the separation area between the absorption region and the top and bottom DBR is also wide-band material. In practice, the mirror is composed by media or 1/4 wavelength of semiconductor materials commonly stack, and in simplified design, the top mirror can be composed of semiconductor materials and air interface that provides about 30% reflectivity. Absorption interlayer is inserted between two end face reflectors, and its thickness is d and its absorption coefficient is α. The space between absorption layer and the top and bottom mirror is represented by L1 and L2, and their absorption coefficient is αex. The reflection coefficient of top and bottom mirror are respectively r1exp (– I ψ 1) and r2exp (– I ψ 2) whereψ1 and ψ2 are the phase shift caused by light transmission reflectors [2]. The transmission of incident light of the electric field Ei is equal to t1-Ei.The electric field component of forward transmission wave Ef is composed of the transmission components and the reflection in the cavity mentioned. In **Figure 1**, the forward transmission optical field Ef at z=0 can be obtained by self-consistency, that is, Ef is sum of the transmission component of the incident light waves and its feedback in the cavity:

$$E_f = t_1 E_i + r_1 r_2 e^{-\alpha d - \alpha_{ex}(L_1+L_2)} e^{-j(2\beta L+\psi_1+\psi_2)} E_f \tag{2}$$

Reverse transmission wave (i.e. Eb at z=L) can be obtained by computing the reflection of forward transmission light wave through cavity mirror:

$$E_b = r_2 e^{-\alpha d/2} e^{-(\alpha_{ex}/2)(L_1+L_2)} e^{-j(\beta L+\psi_2)} E_f \tag{3}$$

Here, the sourced absorption light power (Pl) can be obtained from the incident light power Pi:

$$\begin{aligned} P_l &= (P_f e^{-\alpha_{ex}L_1} + P_b e^{-\alpha_{ex}L_2})(1-e^{-\alpha d}) \\ &= \frac{(1-r_1^2)(e^{-\alpha_{ex}L_1} + r_2^2 e^{-\alpha_{ex}L_2} e^{-\alpha_c L})(1-e^{-\alpha d})}{1-2r_1 r_2 e^{-\alpha_c L}\cos(2\beta L+\psi_1+\psi_2)+(r_1 r_2)^2 e^{-2\alpha_c L}} \times P_i \end{aligned} \tag{4}$$

Assuming that all light-generating carriers contribute to the current of detectors, ηis the ratio of the absorbed light power to the incident light power, that is:η=Pl/Pi, the equation (5) could be concluded that:

$$\eta = \left\{ \frac{(e^{-\alpha_{ex}L_1} + e^{-\alpha_{ex}L_2} R_2 e^{-\alpha_c L})}{1-2\sqrt{R_1 R_2}\, e^{-\alpha_c L}\cos(2\beta L+\psi_1+\psi_2)+R_1 R_2 e^{-2\alpha_c L}} \right\} \times (1-R_1)(1-e^{-\alpha d}) \tag{5}$$

In practical design of detectors, $\alpha_c = (\alpha_{ex}L_1 + \alpha_{ex}L_2 + \alpha d)/L$ is the absorption of material (the absorption comes mainly from free carriers)out of the sourced layer（αex：5~10cm-1）which could be ignored compared with the sourced layer(α≥104cm-1), therefore αex in equation (5) could be omitted, and η could also be presented in following equation：

$$\eta = \left\{ \frac{(1+R_2 e^{-\alpha d})}{1-2\sqrt{R_1 R_2}\, e^{-\alpha d}\cos(2\beta L+\psi_1+\psi_2)+R_1 R_2 e^{-2\alpha d}} \right\} \times (1-R_1)(1-e^{-\alpha d}) \tag{6}$$

The **Figure 2** shows the dependence of η on the wavelengths. The three curves are respectively the three reflectivity of the top mirror, R1=0.9, 0.3, 0.05 (solid line-0.9, dotted line-0.3, broken line-0.05), and other parameters are set (R2=0.9,αd=0.1,L=2μm). η locates periodically at resonance wavelength, that is, 2βL+ψ1+ψ2=2mπ (m=1,2,3…) is enhanced

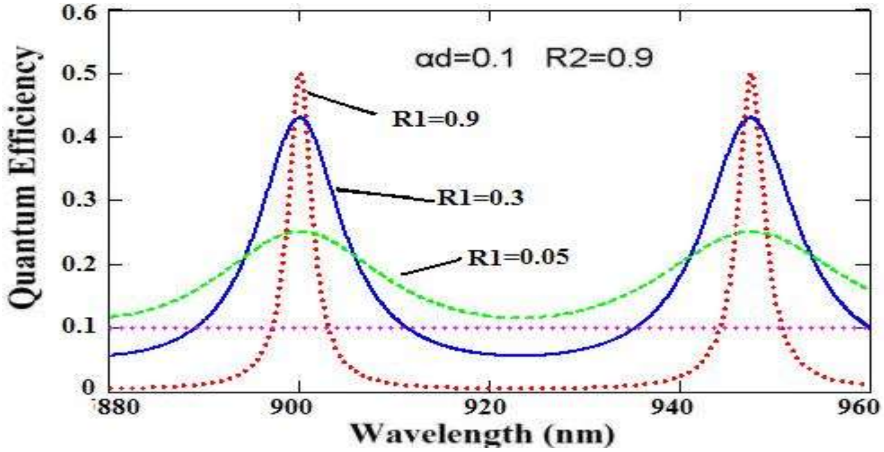


Fig. 2: wavelength dependence of quantum efficiency of RCE component on the variety of reflectivity of top mirrors

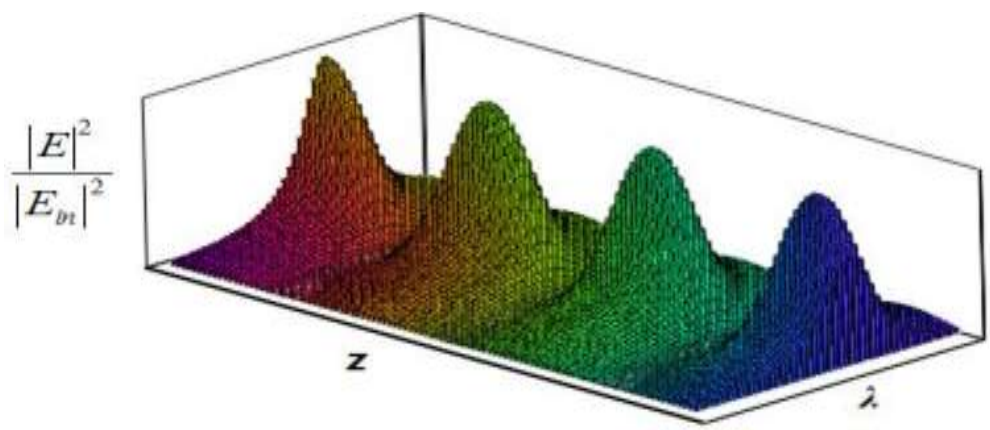


Fig. 3: optical filed distribution of RCE component based on wavelengths

In the equation (6), the parameters within the braces represents the enhancement effect of cavity quantum efficiency. The enhancement factor is 1 when R2 = 0, and this is the quantum efficiency of a traditional detector. The flat dotted line in figure 2 represents the quantum efficiency achieved by traditional optical detectors at the same thickness of sourced layer (q d=0.1). The difference is obvious between the two detectors. Traditional optical detectors have a constant quantum efficiency over a very wide wavelength, the maximum quantum efficiency is not more than 0.1, but RCE photodetector can obtain the quantum efficiency greatly enhanced at a particular wavelength by our design. This is the enhancement of quantum efficiency on a resonant cavity.

The condition for a RCE component to get the maximum of quantum efficiency is R1=R2e-2αd, and the selection of parameters of the component could achieve almost 100% theoretical value of quantum efficiency of RCE PD.

2. Analysis of standing wave effect of RCE components: For two light wave equations (2) and (3) which travel oppositely, the standing waves from their superposition could form a periodical distribution of the intensity of a light field. The quantum efficiency of a component, effected by the intensity of the light filed, could be a position function of sourced layers in a light field, which we call it standing wave effect[5] (SWE). It was SWE that makes wavelength selection and enhancement of RCE components.

The standing effect in the equation of quantum efficiency is an efficient absorption coefficient: αeff （αeff=SWE·α）, which could present enhancement or weakness according to the position of the sourced layer.

$$\alpha_{eff} = \frac{1/d\int_0^d \alpha(z)|E|^2(z,\lambda)dz}{2/\lambda\int_0^{\lambda/2}|E|^2(z,\lambda)dz} \tag{7}$$

Suppose the absorption coefficient could be ignored outside the absorption region and the absorption coefficient is a constant,

$$SWE = \frac{\alpha_{eff}}{\alpha} = \frac{1/d\int_{L_1}^{L_1+d}|E|^2(z)dz}{2/\lambda\int_0^{\lambda/2}|E|^2(z)dz} \tag{8}$$

The forward component（Ef） and backward component (Eb) of the standing wave in the cavity are given by the equations (2) and (3), the total electric field E and its intensity is ：

$$E = E_f(0)\exp(-j\beta z) + E_b(L)\exp[j\beta(z-L)] \tag{9}$$

$$|E|^2 = |E_f(0)|^2 + |E_b(L)|^2 + 2\,\mathrm{Re}\{E_f^*(z)E_b(z)\} \tag{10}$$

Take equations (2) and (4) into the equation (10) and let α=0, we get the equation (11):

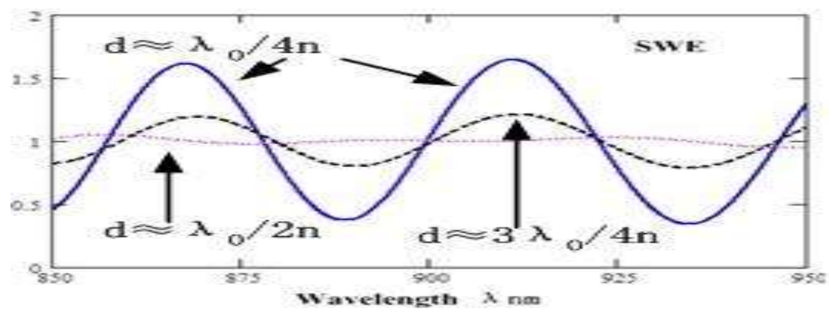
$$|E|^2 = \left\{\frac{|1-r_1^2|}{\left|1-r_1r_2e^{j(2\beta L+\psi_1+\psi_2)}\right|^2}\right\}\times[1+r_2^2+2r_2\cos[2\beta(L-z)+\psi_2]]|E_{in}|^2 \tag{11}$$

The **Figure 3** shows that the intensity distribution in the cavity of a RCE photodetector based on the material of GaAs is dependent on the wavelengths, and the periodical variety of intensity of internal light field with the position and wavelengths of a RCE component. The effect of standing waves are therefore shown.

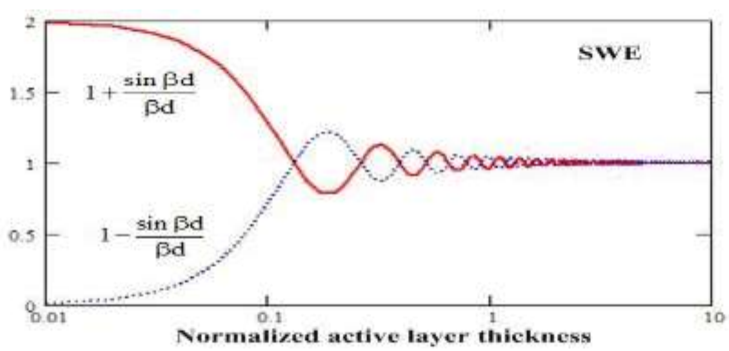
Take the equation (11) into the equation (8), and omit the independent factors with wavelengths, we can obtain the relation of SWE and the parameters of resonance cavity:

$$SWE = 1 + \frac{2r_2}{\beta d(1 + r_2^2)}[\sin \beta d \cos(2\beta L_2 + \beta d + \psi_2)] \tag{12}$$

The **Figure 4** (a) shows the dependence of SWE on wavelengths at the different thickness of the sourced layer. When d≈λ0/4n（solid line）, SWE varies between 0.35 and 1.7, which results in the dramatic variety of the light response of the component to the light in different wavelengths. When d≈λ0/2n dotted line）, the SWE is a little weak, which is because the sourced layer covers half the period. The bottom mirror is composed of GaAs/Al As DBR with 20 periods and the top mirror is composed of GaAs and air interface （L1=L2=2μm）.



(A) Wavelengths



(b) The thickness of standard active layers

Fig. 4: the dependence of SWE on wavelengths and the thickness of absorption

If there is a ideal bottom mirror （r2=1,ψ 2=0）, a real reflectivity of the top bottom （ψ1=0）, and L1=L2(centering the sourced layer), the SWE could be simplified :

$$SWE = 1 + \cos(m\pi)\frac{\sin \beta d}{\beta d} = 1 \pm \frac{\sin \beta d}{\beta d} \tag{13}$$

+ and - in the equation are respectively the maximum and minimum of the standing wave in the center of the sourced layer. The extreme case of SWE is shown in figure 4(b), and the subfigure also shows the reverse variety of SWE with the increasing thickness of the sourced layer.

Analysis of wavelength selection of RCE components: For a RCE component, the amplitude of the light field in a cavity would be reduced due to the interactivity of forward and backward light waves at the location of non-resonance wavelengths (e.g. $2\beta L+\psi 1+\psi 2=(2m+1)\pi$, (m=1,2,3…)), the RCE component could thus only present its high quantum efficiency in a very narrow region near the resonance wavelengths, which is the wavelength selection of RCE components[4]。

CONCLULSION

To sum up, the enhanced photodector of resonant cavity combines skillfully the optical filters and optical-electrical detectors through F - P cavity, and its special structure solves the mutual restriction between quantum efficiency and carrier transit time of ordinary light detectors, and increases greatly the quantum efficiency and response speed. Due to the wavelength selection, the photodetector could apply in many optical-electrical devices such as light detector, light modulator, light emitting diode.

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