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Flat-top steep-edge photodetector with cascaded grating structure

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New type of photodetector with cascaded waveguide grating filters as bottom reflection mirror is proposed. Greatly improved spectral response is shown to follow by the integration of waveguide grating into classical thin-film homogeneous layers. Calculation results for single grating, cascaded-double grating and cascaded-triple grating structure are demonstrated. An increasing rectangular spectral response is obtained by cascade two or three grating filters. Compared with traditional photodetector with distributed Bragg reflectors (DBRs), this new type of photodetector with the same materials require significantly fewer layers while maintaining narrow flat-top response, high peak efficiency and low sideband reflectance. © 2009 Optical Society of America

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1. Introduction

Resonant cavity enhanced (RCE) photodetector is widely used in optical fiber communication with a characteristic of high-speed, high quantum efficiency and high sensitivity [1]. To fully benefit from the RCE scheme in fiber communications, the peak of quantum efficiency has to match the source wavelength. Slightly fluctuation in the source wavelength would cause a tremendous fluctuation in the detection efficiency. To overcome the disadvantages of RCE photodetector mentioned above, it is quite desirable to design a new structure of photodetector with a narrow spectral response linewidth, at the same time detect all sources emitting in a particular communication window with a constant efficiency. A feature of flat-top and steep-edge response is required in order to get high detection efficiency under the condition of slightly fluctuation in the source wavelength.

Several methods to realize the flat-top and steep-edge response have been investigated. Design examples include introducing an anomalous-dispersion region in the reflection phase of the top mirror [2], depositing a half-wave thickness layer into the DBR [3] and cascading two or three FP cavity together [4]. In [2] the experimental result of the quantum efficiency of the flat-top steep-edge photodetector is 0.8 at 1550nm and a full width half maximum (FWHM) is 35.96nm. However, according to the applicable requirements, both the theoretical simulation and experimental result is not acceptable to wavelength-division multiplexing (WDM) systems. In [3] a device with a wavelength of 850nm is described, but a detailed analysis and the trade-offs among the various parameters are not given. The method of achieving the flat-top response in [4] is simple and easy to fabricate, but the FP cavity is so long and precision is so difficult to control that it is hard to be applied into optical electronic integrated devices.

2. Design and Simulation

A stack of waveguide grating reflection elements is demonstrated in Fig.1. It consists of the upper layer and the substrate with reflective indices of n_c and n_s respectively. A grating region of thickness of d_g with high and low indices n_H and n_L is sandwich between the upper layer and the homogeneous layer 1. The value of grating period Λ is set according to the rule that only the zero order and both the +1 and -1 diffracted order are permitted to propagate in the upper layer and substrate region. All other diffracted orders are evanescent. The function of homogeneous layers is to improve the symmetry of the spectral response. The response of the cascaded elements can be treated in a way similar to that of the reflective feature of a dielectric homogeneous layer. The incident light to the waveguide grating structure assumes a TE-polarized, normal incident plane wave, and the calculation are performed with rigorous coupled-wave analysis (RCWA) theory [5, 6].

New type of photodetector with single waveguide grating filters as bottom reflection mirror is depicted in Fig.5, and its spectral response is sketched in Fig.6. The top mirror be fabricated by means of wet chemical etching and the inclined mirror can be formed by depositing 2 periods of Si/SiO_2 DBR. The reflectivity of the top mirror as a function of the wavelength is sketched in Fig.4. Its spectral reflectance is 0.87 in the range of wavelength from 1500nm to 1600nm. The top mirror reflectivity should not be unity, as no light will be transmitted to the cavity and the quantum efficiency will be zero. We obtain the bottom mirror by embedding binary grating between two homogeneous layers. This grating is called embedded grating, though more difficult to fabricate than a surface-relief grating, this cascaded waveguide grating structure can be fabricated through the method similar to that of grating. The average dielectric index of grating layer has to be higher than the cover and substrate dielectric indexes for the waveguide resonance to occur [7]. The thickness of the waveguide grating is important to determining the feature of reflectance such as sideband ripples, linewidth, and free spectral range. The symmetric line-shape reflection can be attained by choosing the grating thickness and the homogeneous layer to be multiple of quarter-wavelength. i.e., the grating thickness $d_g = m\lambda_{grat}/4\sqrt{\varepsilon_{equ}}$, where $\varepsilon_{equ} = (\varepsilon_H + \varepsilon_L)/2$, ε_H and ε_L are the high and low relative permittivity of grating respectively, λ_{grat} is a resonance wavelength, and m=2,4,6….. The thickness of the homogeneous $d_1 = \lambda_{grat}/4\sqrt{\varepsilon_1}$, $d_2 = \lambda_{grat}/4\sqrt{\varepsilon_2}$, where ε_1 and ε_2 are the relative permittivity of the of layer 1and layer 2 respectively [8]. The resonance wavelength is set by the value of the grating period, and the waveguide geometry is symmetric with the relative permittivity of the cover equal to that of the substrate.

There exist two methods to calculate the quantum efficiency of the photodetector: one is an analytical formulation presented by M.S. Unlu *et al.* in 1991, and the other is transfer matrix method (TMM). The top mirror and the bottom grating filters reflectivities and phase angles are calculated by TMM. The mirror reflectivities and reflectance phases are used to determine the light-field distribution inside the lossy cavity considering the whole RCE structure following the approach present by [1]. The quantum efficiency is the ratio of the absorbed power to the incident optical power, can be written:

$$\eta = \frac{(1 + R_2 \exp(-\alpha d))}{1 - 2\sqrt{R_1 R_2}\exp(-\alpha d)\cos(2\beta + \psi_1 + \psi_2) + R_1 R_2 \exp(-\alpha d)} \times (1 - R_1) \times (1 - \exp(-\alpha d)) \qquad (1)$$

Where R_1 and R_2 denote the power reflectivity of the top mirror and grating filters respectively, ψ_1 and ψ_2 are phase shifts due to light penetration into the mirror. α is the absorption coefficient, d is the thickness of the active layer. Because the propagation constant β ($\beta = 2n\pi/\lambda_0$, where λ_0 is the vacuum wavelength and n is the refractive index) has a wavelength dependence.

The enhancement of optical power can be calculated by the internal optical power to the incident power. The quantum efficiency of photodetector is obtained multiplying the internal optical power enhancement factor by $(1-\exp(-\alpha d))$ [1]. As αd increase, the enhancement of optical power falls off rapidly, as shown in Fig.2. This is due to the reason that most of the light is absorbed in the active layer before it reaches the grating filters, preventing the optical feedback mechanism necessary for detection. The value of the active layer should be chosen properly. Too thin of it is not desirable because of the reduction in bandwidth due to RC constant limitations. However, too thick of it will reduce the speed of the response and result in poor quantum efficiency. For a given value of R_1 and R_2, there exists one value of d that maximizes the quantum efficiency. As shown in Fig.3, for a given value of top mirror reflectivity, the maximum the quantum efficiency can be determined as a function of αd . A detailed analysis has been discussed by M.S. Unlu *et al.*

The materials used in the design of the grating photodetector are described as follow:

1) The top mirror of the photodetector is made of three pairs of Si/SiO_2 with the thickness of 112nm and 263nm respectively.
2) The thickness of waveguide grating structure is d=119nm, the grating period is Λ=487nm, the refractive indices are n_H =3.4, n_L =3.1, and the fill factor is 0.5.
3) The materials of the homogeneous layers are made of $Ga_{0.47}In_{0.53}As_{0.68}P_{0.32}$ and $Ga_{0.47}In_{0.53}As_{0.33}P_{0.67}$, and the optical thicknesses of them are $\lambda/4-\lambda/4$ at 1550nm, with the refractive indices are 3.4145 and 3.2535 respectively.
4) The thickness of separation layer (InP) is $\lambda\times1.77$ with the refractive index of 3.1.
5) The substrate is InP.

3. Results and Discussion

The refractive indices used in the design of the photodetector correspond to materials commonly used in the fabrication of the semiconductor devices. The response of the photodetector can be attributed to both waveguide grating resonance and thin-film interference effects. There is strong coupling effect between the external propagating wave and adjacent evanescent waves, this affects rapid variation in the reflection. The ratio of the spectral bandpass is a feature to gauge the flatness of a response and is defined as the ratio of the linewidth at an efficiency of 90% ($\Delta\lambda_{0.9}$) to the linewidth at an efficiency of 10% ($\Delta\lambda_{0.1}$). Cascading two or three waveguide grating structures in this manner results in respective an increase in the spectral response bandpass ratio of three times and more than five times that of a single grating photodetector.

As can be seen from Fig.5-Fig.10, compared with the traditional photodetector with DBRs, a significantly fewer layers is required to achieve the same spectral linewidth a peak quantum efficiency. The grating combines with the thin-film coating can reduce the reflectance in the sidebands to arbitrarily low values and extend over a large wavelength range.

The requirement of $\varepsilon_{equ}^2\varepsilon_2^2/\varepsilon_1^2=\varepsilon_c\varepsilon_s$ must be satisfied in order to obtain an ideal reflection response. Where ε_c and ε_s are the relative permittivity of the cover and substrate respectively. From the above analysis, we know that the thickness of the grating layer and the thickness of the homogeneous layer obey the condition that any shift from the set value, the output efficiency deteriorates rapidly. We determine the response of the system by summing the external field contributions resulting from the multiple reflections between the grating structure elements. The sum of phase shift as the incident wave propagates through the grating region and the homogeneous layer is [9]

$$\delta = 2(\delta_{grat}+\delta_{n1}+\delta_{n2}+\delta_{sep}) \tag{2}$$

Where

$$\delta_{grat,n1,n2,sep}=\frac{2\pi}{\lambda}n_{grat,n1,n2,sep}d_{grat,n1,n2,sep} \tag{3}$$

When $\delta = 2m\pi$ (m is an integer), the bottom elements of the photodetector are in phase, whereas on the condition of $\delta=(2m+1)\pi$, the bottom elements of the photodetector are out off phase. The simulation has been convinced that the out off phase layout produce the profile of linewidth exhibit broadened peak efficiency and narrower base as compared with the in phase grating elements. The thickness of the separation layer should be on the order of incident wavelength so that the fields propagating within each part of bottom elements of photodetector considered uncoupled. It also indicates that the cascaded grating elements result in suppressed reflection of the off-resonance wavelength. This result is expected, because the response of two or three cascaded grating elements is approximately equal to the sum of the individual response, the result Fig.8 and Fig.10 convinces that expect.

4. Conclusion

The proposed RCE photodetector is wavelength selective due to the nature of grating filters. The stop-band width of the grating filters plays an important role in selecting different channels in WDM applications. The advantages of this design method over other schemes are that it can obtain a narrower spectral linewidth and a steep-edge response. Due to the reduced thickness a simple design and mature fabrication techniques, this type of photodetector can be a good candidate in the WDM systems.

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Figure Caption Page

Fig.1. The schematic of grating structure with rectangular-index profile of High n_H=3.4 and low n_L=3.1 indices with period Λ=487nm and thickness d=119nm (quarter-wave at λ=1550nm)

Fig.2. The power enhancement factor as a function of αd

Fig.3. The quantum efficiency as a function of αd at the condition of the grating filters reflectivity R_2=0.99 and as a function of top mirror reflectivity R_1

Fig.4. Top mirror reflectivity as a function of the wavelength

Fig.5. Schematic diagram of single waveguide grating photodetector consisting of a p-i-n photodiode sandwiched between the DBR mirrors and waveguide grating filter

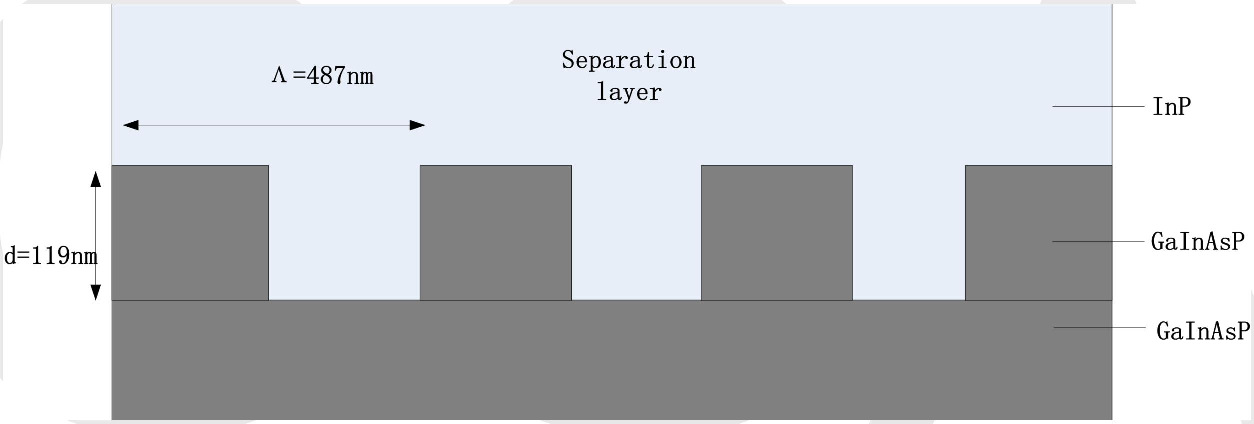
Fig.6. The quantum efficiency of single waveguide grating photodetector centered at 1550nm, $\Delta\lambda_{0.9}/\Delta\lambda_{0.1}$=0.12, FWHM=1.26nm

Fig.7. The structure of cascaded double waveguide grating photodetector consisting of a p-i-n photodiode sandwiched between the DBR mirrors and waveguide grating filter

Fig.8. The quantum efficiency of cascaded double waveguide grating photodetector centered at 1550nm, $\Delta\lambda_{0.9}/\Delta\lambda_{0.1}$= 0.34, FWHM=1.729nm

Fig.9. The structure of cascaded triple waveguide grating photodetector consisting of a p-i-n photodiode sandwiched between the DBR mirrors and waveguide grating filter

Fig.10. The quantum efficiency of cascaded triple waveguide grating photodetector centered at 1550nm, $\Delta\lambda_{0.9}/\Delta\lambda_{0.1}$= 0.63, FWHM=1.591nm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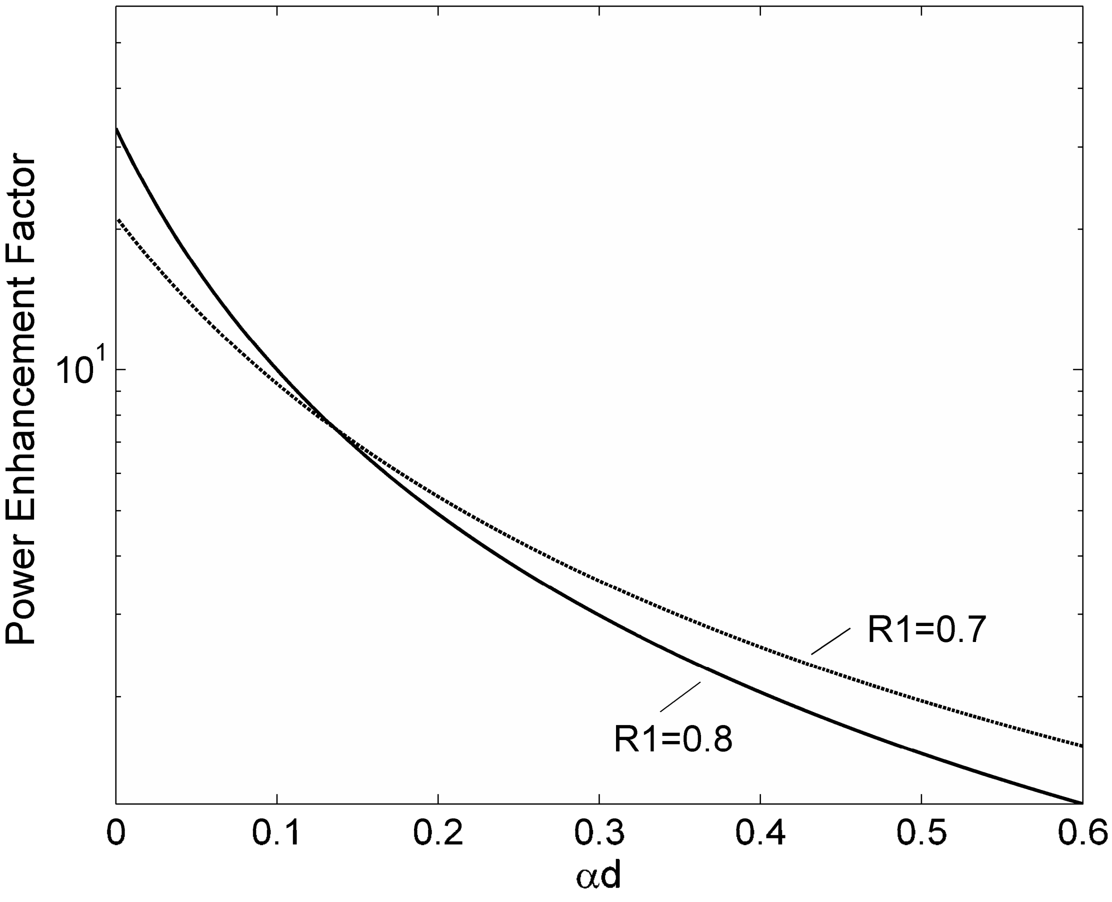
InP
d=119nm
GaInAsP
GaInAsP


Power Enhancement Factor
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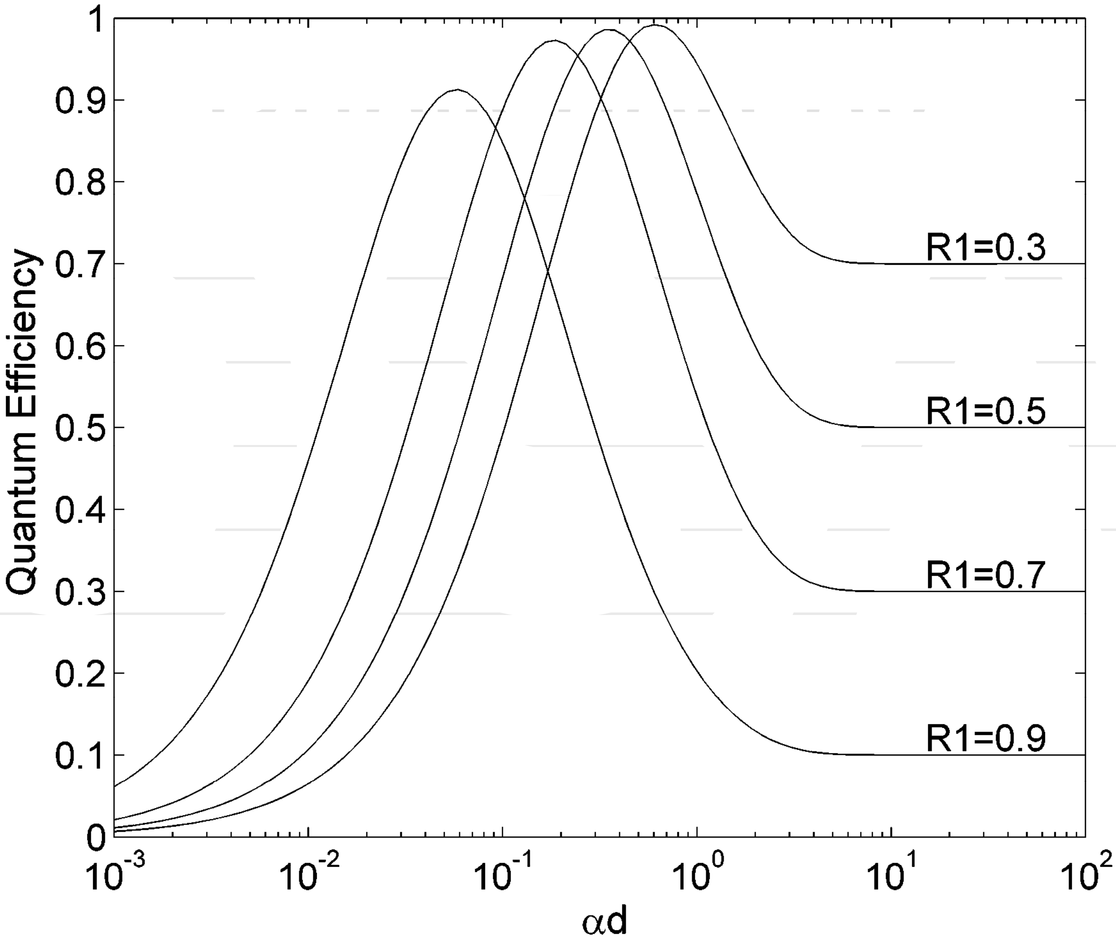
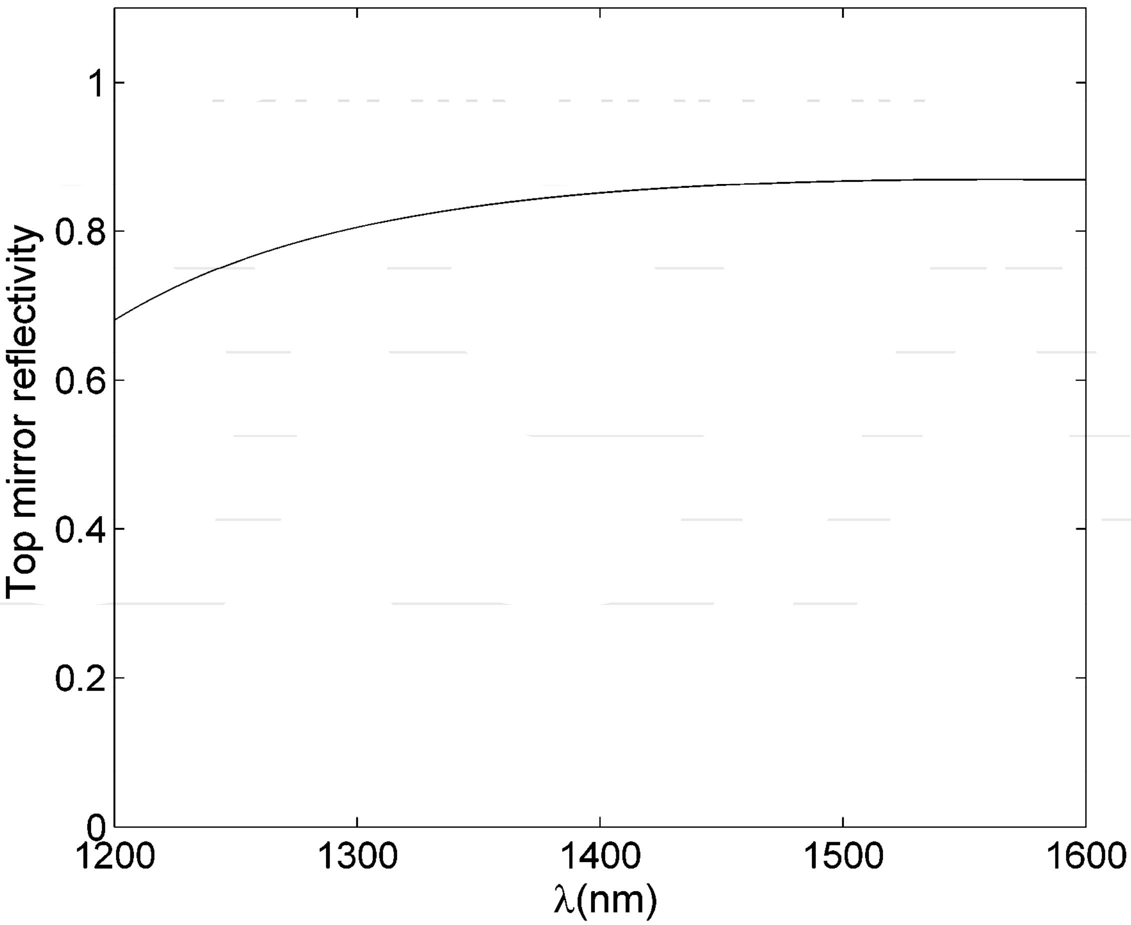
0.2
0.3
0.4
0.5
0.6
αd
R1=0.7
R1=0.8



Quantum Efficiency
αd
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
R1=0.3
R1=0.5
R1=0.7
R1=0.9


Top mirror reflectivity
1
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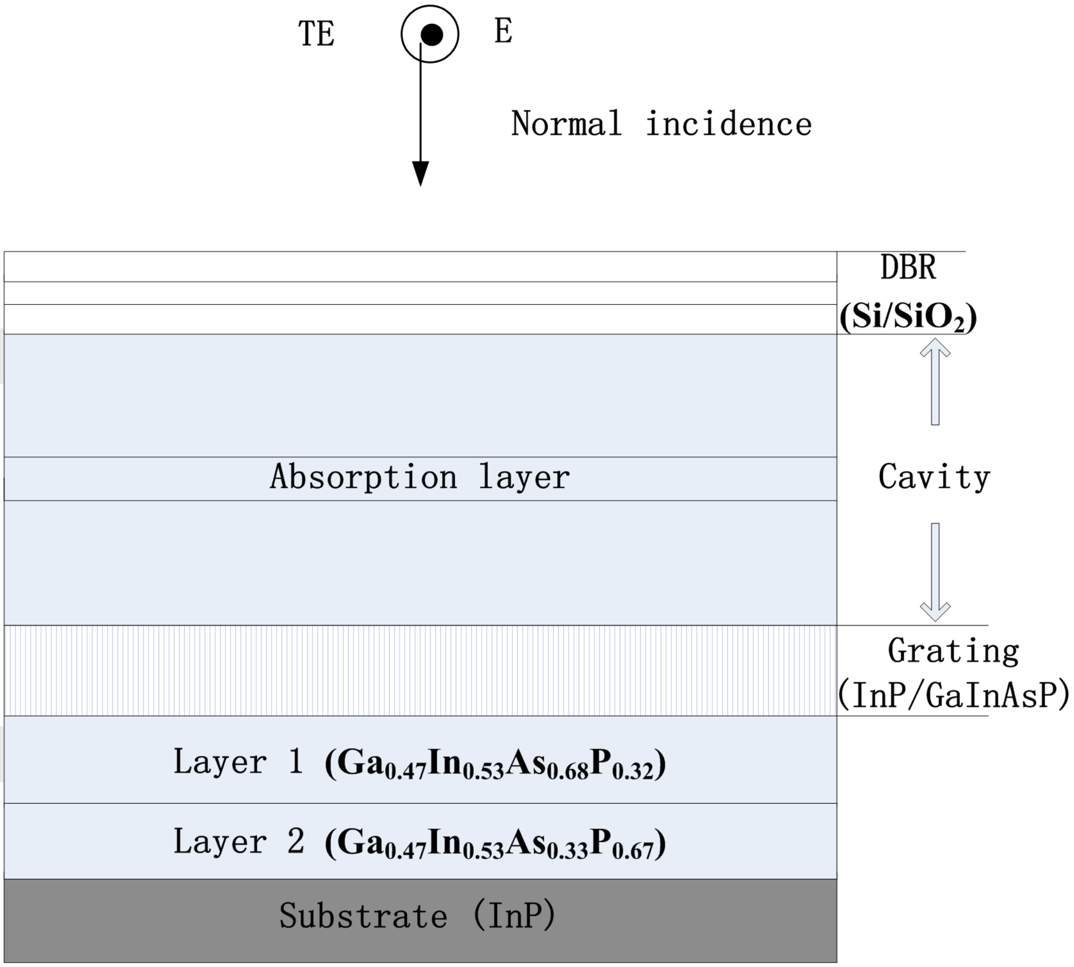
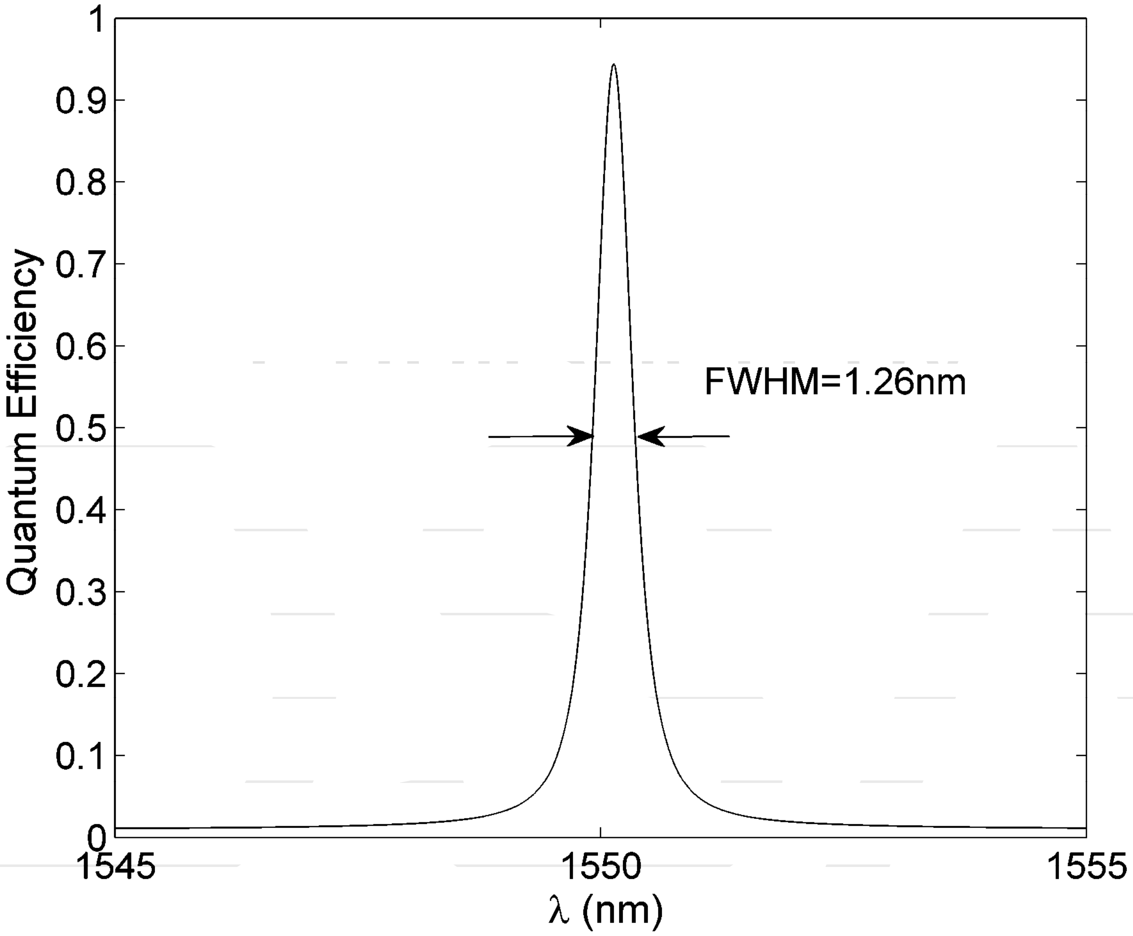
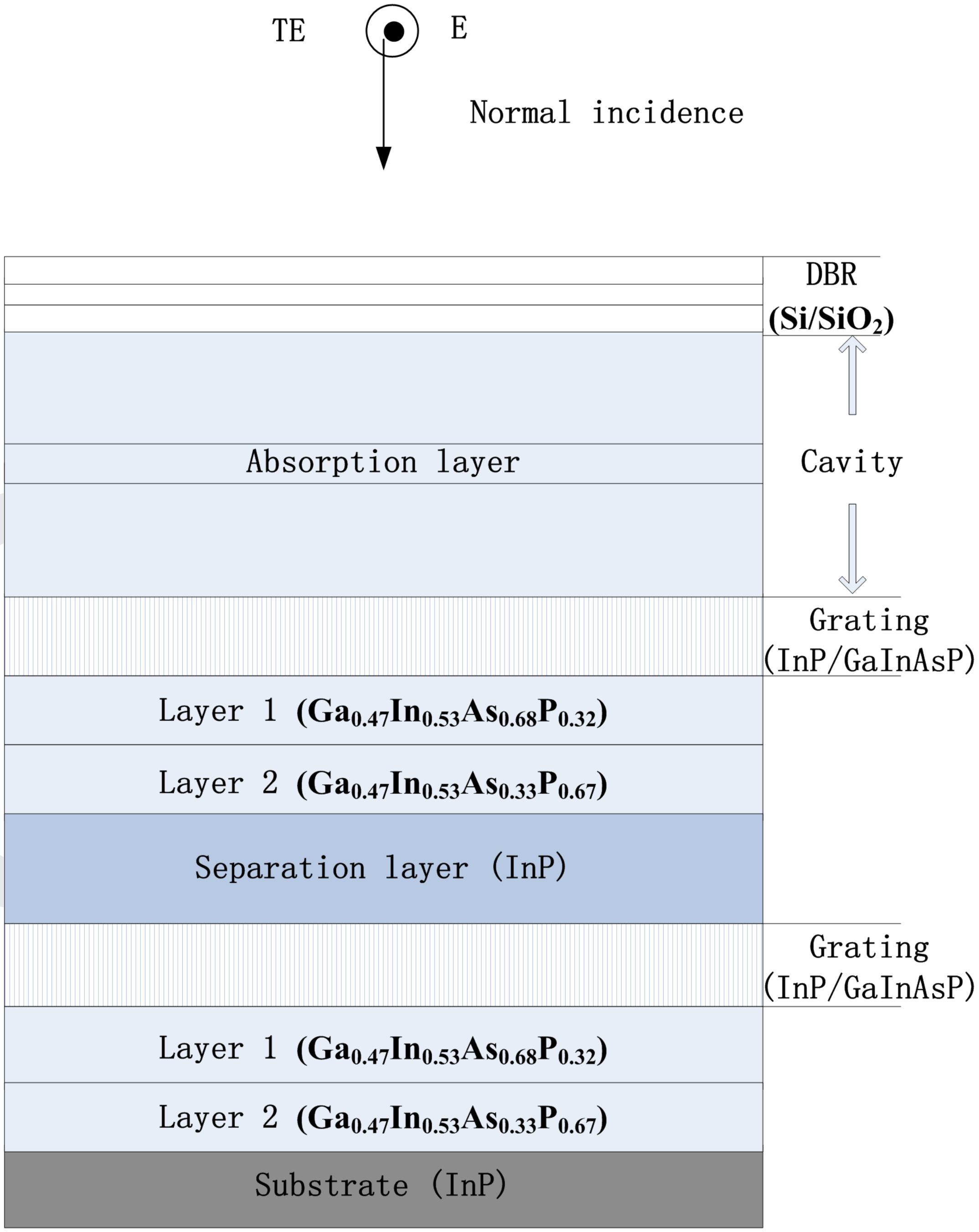
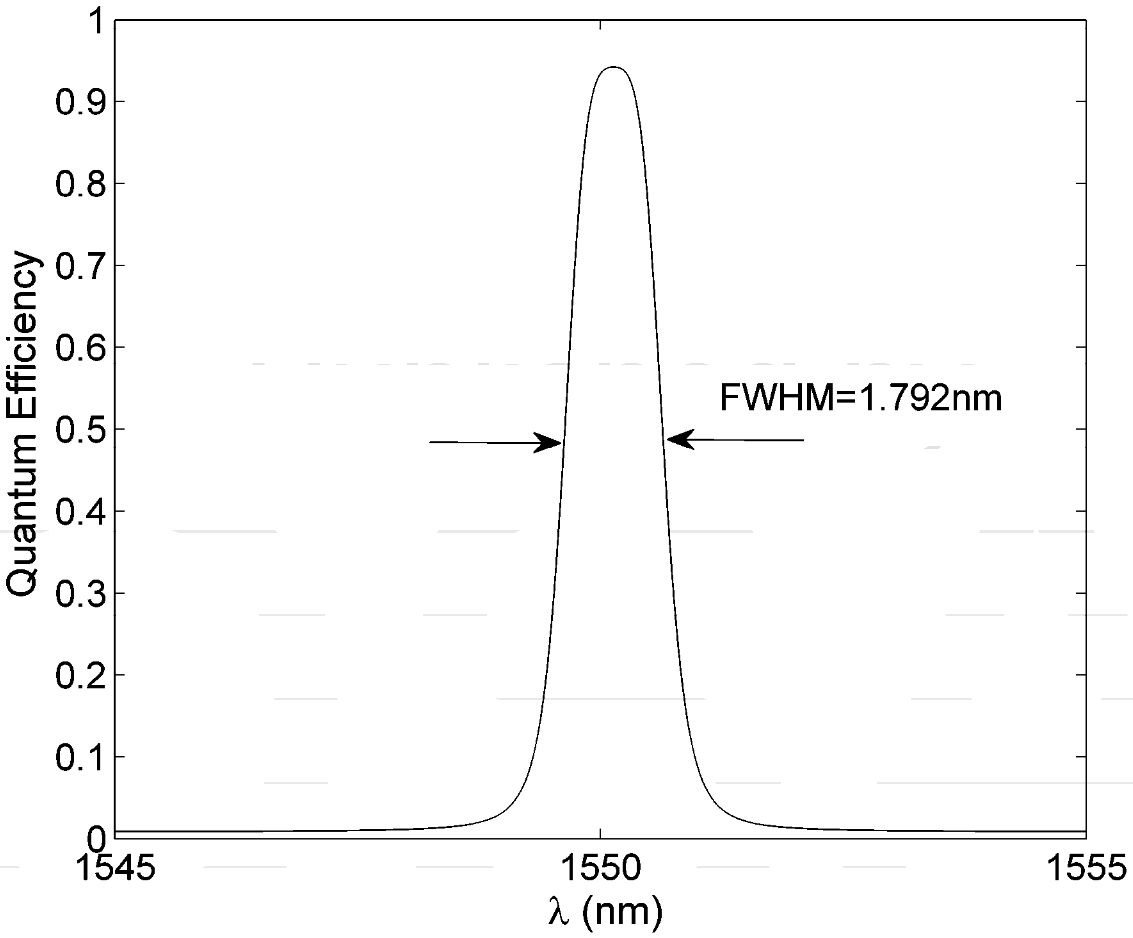
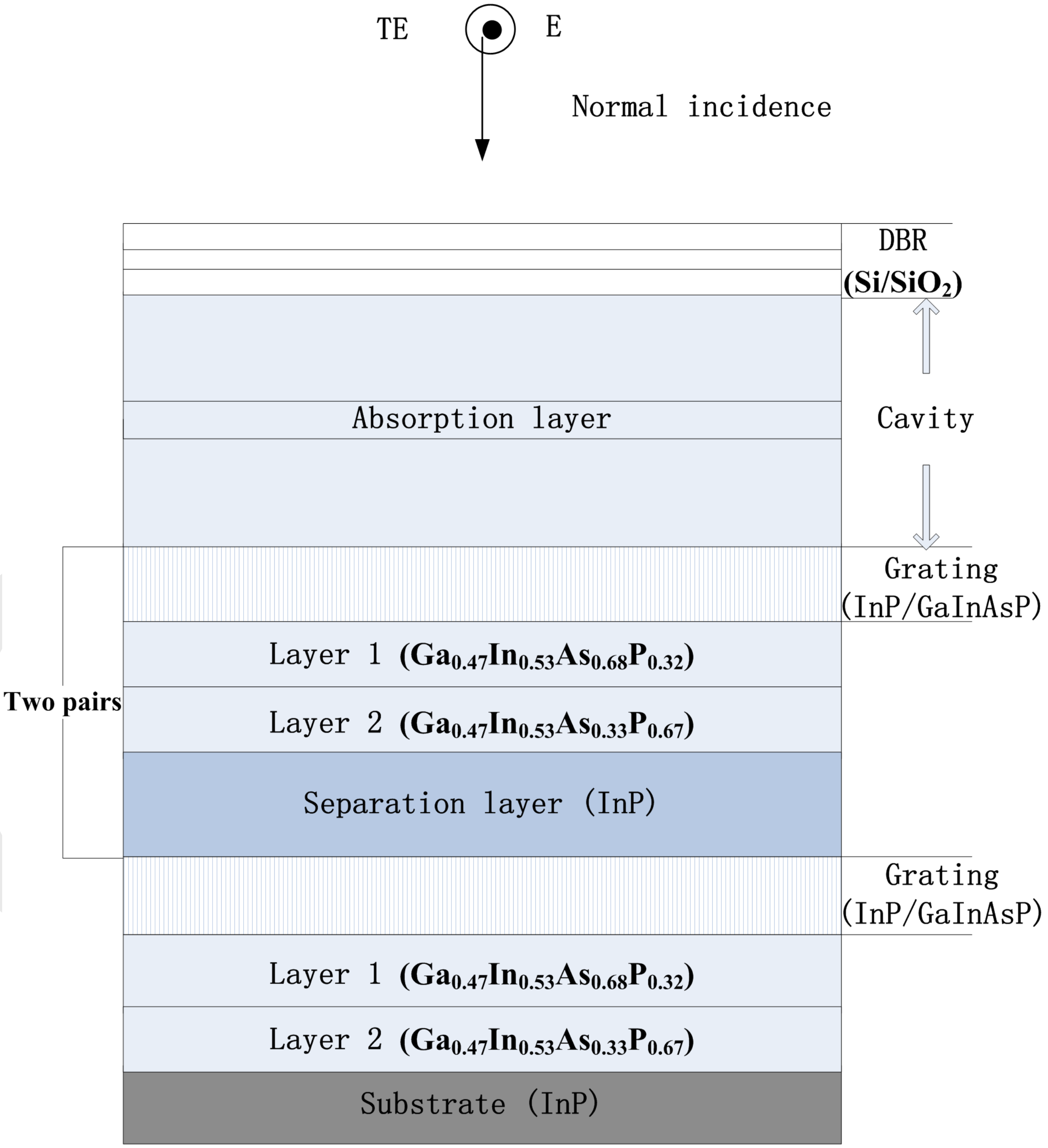
0.6
0.4
0.2
0
1200
1300
1400
1500
1600
λ(nm)

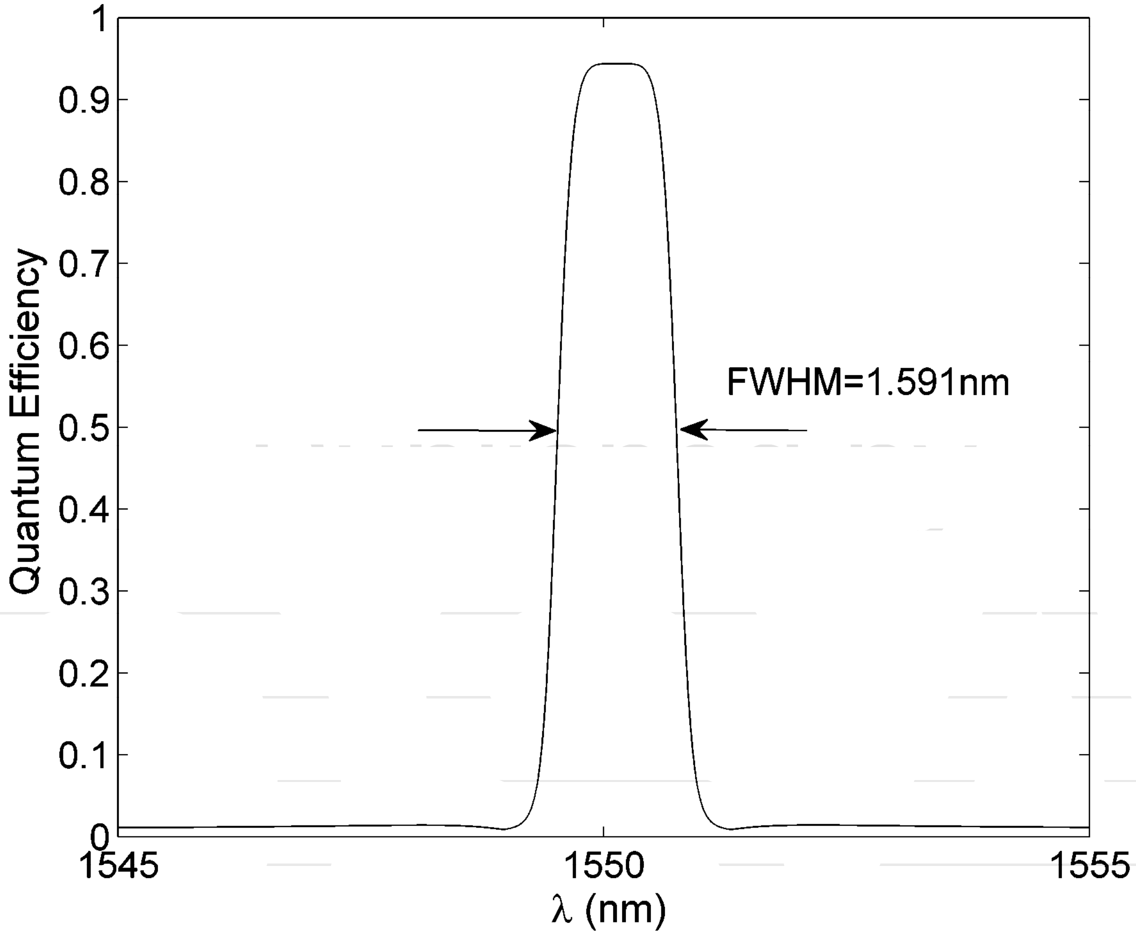

TE
E
Normal incidence
DBR
(Si/SiO$_2$)
Cavity
Absorption layer
Grating
(InP/GaInAsP)
Layer 1 (Ga$_{0.47}$In$_{0.53}$As$_{0.68}$P$_{0.32}$)
Layer 2 (Ga$_{0.47}$In$_{0.53}$As$_{0.33}$P$_{0.67}$)
Substrate (InP)


Quantum Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1545
1550
1555
λ (nm)
FWHM=1.26nm


TE
E
Normal incidence
DBR
(Si/SiO$_2$)
Cavity
Absorption layer
Grating
(InP/GaInAsP)
Layer 1 (Ga$_{0.47}$In$_{0.53}$As$_{0.68}$P$_{0.32}$)
Layer 2 (Ga$_{0.47}$In$_{0.53}$As$_{0.33}$P$_{0.67}$)
Separation layer (InP)
Grating
(InP/GaInAsP)
Layer 1 (Ga$_{0.47}$In$_{0.53}$As$_{0.68}$P$_{0.32}$)
Layer 2 (Ga$_{0.47}$In$_{0.53}$As$_{0.33}$P$_{0.67}$)
Substrate (InP)


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Quantum Efficiency
FWHM=1.792nm
1545
1550
1555
λ (nm)


TE
E
Normal incidence
DBR
(Si/SiO_2)
Cavity
Absorption layer
Grating
(InP/GaInAsP)
Two pairs
Layer 1 **($Ga_{0.47}In_{0.53}As_{0.68}P_{0.32}$)**
Layer 2 **($Ga_{0.47}In_{0.53}As_{0.33}P_{0.67}$)**
Separation layer (InP)
Grating
(InP/GaInAsP)
Layer 1 **($Ga_{0.47}In_{0.53}As_{0.68}P_{0.32}$)**
Layer 2 **($Ga_{0.47}In_{0.53}As_{0.33}P_{0.67}$)**
Substrate (InP)


Quantum Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1545
1550
1555
λ (nm)
FWHM=1.591nm