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基于多圆环谐振腔 MIM 波导多路分频特性

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摘 要:在可见光到近红外频段,利用时域有限差分数值模拟计算方法,研究了一种多圆环形金属-介质-金属等离子体波导结构的电磁传输特性.结果表明,由于谐振作用,不同波长电磁波能量被分别束缚于圆环中,之后被耦合到各出口端进行传输,从而实现了电磁波的多路分频传输功能.圆环的共振波长与圆环半径之间存在近似线性关系,且随着圆环内填充介质折射率的增大呈现明显的红移现象;各出口端共振波长对应电磁能量的传输率随着介质波导与圆环间耦合厚度的增大而急剧降低.利用电磁波共振理论阐述了电磁能量的谐振束缚现象,与数值模拟结果吻合.研究结果可应用于未来光子集成器件中.

关键词:金属-介质-金属波导;多路分频;传输;时域有限差分方法;光学器件

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Demultiplexing Characteristic of MIM Waveguide Based on Multiple-Ring Shaped Resonators

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Abstract: A multiple-ring shaped Metal-Insulator-Metal (MIM) plasmonic waveguide with multi-output ports was proposed. From visible lightto nearinfrared wavelengths, the transmission characteristics of the structure were investigated by finite-difference time-domain method. The structure exhibits typical wavelength demultiplexing function, which is due to that the electromagnetic wave energy of different wavelengths can be trapped in different insulator rings and coupled into the corresponding output ports. The resonance theory is employed to analyze the trapping phenomenon. The resonant wavelength of the ring has near linear relationship with the radius and has red shift with increase the value of the filled refractive index. The transmittance of resonant wavelength in the output ports are heavily influenced by the coupled thickness. The proposed multiple-ring shaped MIM waveguide may be useful for plasmonic designs.

Key words: Metal-insulator-metal waveguide; Demultiplexing; Transmission; Finite-difference time-domainmethod; Optical devices

OCIS Codes: 230.7408; 050.6624; 240.6680

0 Introduction

Electromagnetic waves couple with free electron oscillations propagate at metal-insulator interfaces, known as Surface Plasmon Polaritons (SPPs), has been considered as the most potential way to realize highly integrated optical circuits, because it can carry energy and information to overcome the diffraction limit of light[1]. Plasmonic waveguide structures have drawn many attentions for prospect of photonic integration. Two kinds of SPPs waveguides, the Metal-Insulator-Metal (MIM) structure[1] and the Insulator-Metal-Insulator (IMI) structure[2], have been widely investigated. Compared with the IMI waveguide, the

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MIM waveguide has smaller mode size, stronger confinement of light, shorter propagation length and easier to fabrication[3]. Therefore, the MIM waveguide has been vigorously researched in recent years. Many components based on MIM waveguide, such as couplers[4], Bragg reflectors[5-6], all-optical switcher[7-8], trapping system[9-11] and plasmonic filter[12-16] have been numerically or experimentally demonstrated.

The wavelength demultiplexer can separate wave spectrum into different frequencies, which has great potential applications in photonic integrations. In recent years, the MIM waveguides have been proposed to achieve the demultiplexing function, such as the arrayed slot cavities[17], nanodisk resonators[18], side-coupled nanodisk cavities[19] and T-shaped[20] MIM waveguides. In this paper, a plasmonic structure based on multiple-ring shaped MIM waveguide with multi-output ports is proposed. From the visible to near-infrared wave band, the transmission characteristics are investigated using Finite-Difference Time-Domain (FDTD) method with Perfectly Matched Layers (PML) absorbing boundary condition. The results show that the proposed structure has typical wavelength demultiplexing function. The electromagnetic wave energy of different wavelengths can be trapped in different insulator rings and coupled into the corresponding output ports. The resonance theory is employed to analyze the trapping phenomenon.

1 Model and method

Fig. 1 depicts the schematic of a two-dimensional (2D) wavelength demultiplexing multiple-ring shaped MIM waveguide with multi-output ports. The materials in the grey and white areas are set to be silver and air. The frequency-dependent complex relative permittivity of Ag is referred to Ref. [21]. The width

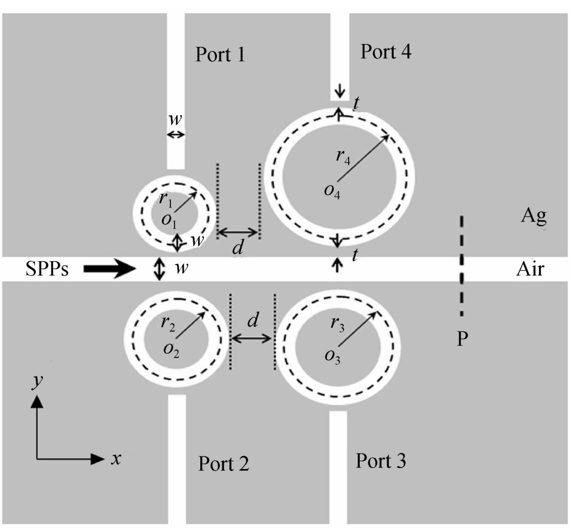


Fig. 1 Schematic of the wavelength demultiplexing multiple-ring shaped MIM waveguide structure with multi-output ports

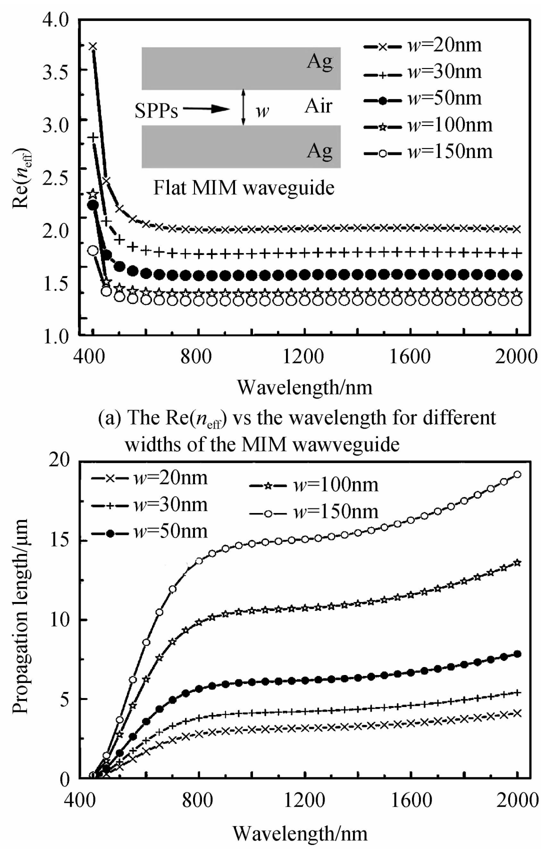
of air channel is $w=50$ nm with relative permittivity $\varepsilon_d=1$. The distance of the two rings on one side of the waveguide is $d=150$ nm. The thickness of the silver between the waveguide and ring is $t=10$ nm. The air ring $O_i(i=1,2,3,4)$ with radius r_i is the average of the outer and inner radii. The corresponding circumference of the ring $L_i=2\pi r_i$ is as depicted by the dashed line.

Since the width of the air channel is much smaller than the incident wavelength , only the fundamental TM mode wave is excited in the structure, whose dispersion relation is determinedas[22]

$$\varepsilon_d k_m+\varepsilon_m k_d \tanh\left(\frac{k_d}{2}w\right)=0 \tag{1}$$

where ε_m and ε_d are dielectric constants of the metal and insulator , k_m and k_d defined as $k_m=\sqrt{\beta^2-\varepsilon_m k_0^2}$ and $k_d=\sqrt{\beta^2-\varepsilon_d k_0^2}$ respectively. β designates the constant of propagation for SPPs and $k_0=2\pi/\lambda$ is the wave vector of light with wavelength λ in free-space. The effective refractive index of the waveguide is represented as $n_{\mathrm{eff}}=\beta/k_0$.

From the dispersion relation, the relationship between the n_{eff} and incident wavelength for different widths of the flat MIM waveguide, as shown in the insert of Fig. 2(a), can be obtained. Fig. 2(a) exhibits



(a) The Re(n_{eff}) vs the wavelength for different widths of the MIM wawveguide

(b) The propagation length vs the wavelength for different widths of the MIM wawveguide

Fig. 2 The Re (n_{eff}) and propagation length versus the wavelength for different widths of the MIM waveguide, respectively the dependency relations of the real part of the effective indexes Re ($n_{\rm eff}$) and the wavelength at different channel widths. It shows that Re ($n_{\rm eff}$) decreases rapidly with the increase of wavelength in the visible light range and then tends to saturate. Fig. 2(b) shows the propagation lengths of SPPs, which are dependent on the imaginary part of $n_{\rm eff}$. It is defined as the length over which the power is carried by the wave decays to 1/e of its initial value, $L_{\rm spps}=\lambda_0/[4\pi{\rm Im}(n_{\rm eff})]$. It can be seen that the smaller insulator channel has shorter propagation length at the same wavelength.

In the following simulation, the 2D FDTD method with PML absorbing boundary condition is employed tocalculate the interplay between incident waves and the proposed MIM waveguide. The spatial mesh steps are set $\Delta x=\Delta y=5$ nm and the time step is set $\Delta t=\Delta x/2c$, where c is the velocity of light in vacuum. The incidentlight transmits along the x direction with TM polarization, as shown in Fig. 1. The transmitted power flows, which are defined as $P=\left[\int {\rm Re}(E\times H)\,{\rm d}S\right]/2$, are recorded as a function of time and finally Fourier transformed to obtain the transmission spectra of the structure.

2 Results and discussion

To study the transmission characteristics of the proposed wavelength demultiplexing plasmonic MIM waveguide structure, the radii r_1, r_2, r_3, r_4 of the rings O_1, O_2, O_3, O_4 are fixed to 85 nm, 105 nm, 125 nm and 140 nm, respectively. When the incident electromagnetic waves transmit along the waveguide, the transmission spectrum of the structure is shown in Fig. 3, which is gotten at position P. It can be seen that there are six transmission troughs which are marked as Ⅰ, Ⅱ, Ⅲ, Ⅳ, Ⅴ and Ⅵ. The corresponding wavelengths of these troughs are 835 nm, 1 009 nm, 1 184 nm, 1 380 nm, 605 and 692, respectively. The transmission efficiency of the electromagnetic waves corresponding to the troughs is low. It implies that the wavelength energy of the troughs are trapped in the air rings and/or transmitted in the output waveguide through port j ($j=1, 2, 3, 4$).

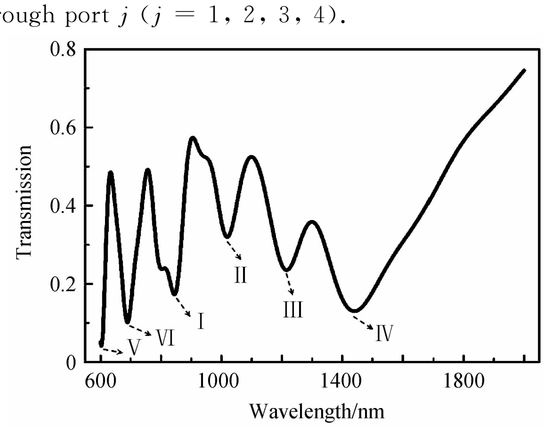


Fig. 3 The transmission spectrum of the demultiplexing plasmonic MIM waveguide

To illustrate the transmission characteristics of the proposed multiple-ring shaped MIM waveguide clearly, the transmission spectra of each output port of the structure are obtained as shown in Fig. 4. It shows one transmission peak for port 1 and port 2, two transmission peaks for port 3 and port 4. Compare the transmission spectra of Fig. 4 with Fig. 3, it can be seen that the wavelengths of the transmission peaks of these output ports are consistent with the transmission troughs in Fig. 3 which are marked as Ⅰ, Ⅱ, Ⅲ, Ⅳ, Ⅴ and Ⅵ. From Fig. 4, we can conclude that the proposed multiple-ring shaped plasmonic MIM waveguide can realize the wavelength demultiplexing function. It should be noted that the transmission troughs Ⅴ and Ⅵ are the second resonance of the rings O_3 and O_4 respectively, as shown in the transmission spectra of port 3 and port 4.

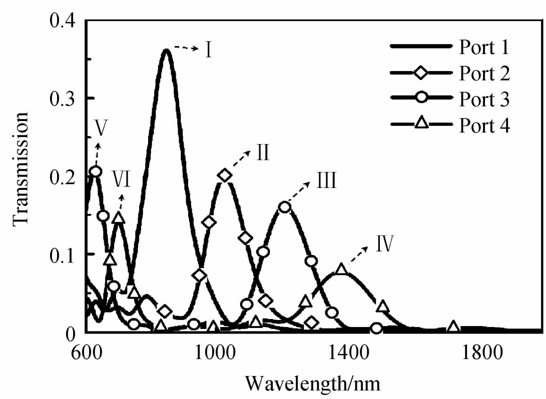


Fig. 4 The transmission spectra of each output port of the demultiplexing plasmonic MIM waveguide

To confirm the wavelength demultiplexing function of the MIM waveguide, the magnetic field intensity $|H_z|^2$ distribution corresponding to the wavelengths of Ⅰ, Ⅱ, Ⅲ and Ⅳ. are displayed in Figs. 5(a)~(d). It shows that the electromagnetic energy of wavelengths 835 nm, 1 009 nm, 1 184 nm,

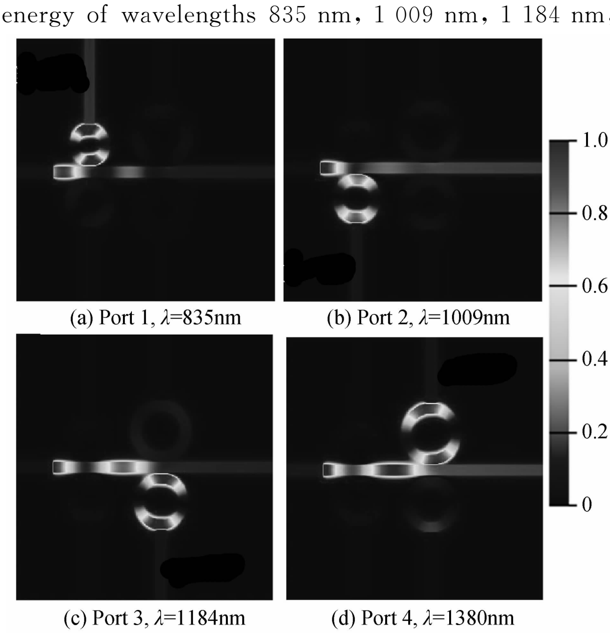


Fig. 5 The distribution of magnetic field $|H_z|^2$

1 380 nm are coupled into the rings O_1, O_2, O_3, O_4, respectively, and transmitted in port 1, port 2, port 3, port 4. It means that most electromagnetic energy of these wavelengths are not transmitted through the waveguide directly, but independently coupled into the corresponding rings and transmitted in the output ports. Fig. 5 also implies that the subwavelength rings can be regarded as resonators and different waves can resonate in different rings.

In theory, the thickness of Ag between the subwavelength waveguide and insulator rings is $t=$ 10 nm. When electromagnetic waves transmit in the waveguide, parts of energy can be coupled and propagated in the rings. The propagation characteristic of waves in the rings is dependent on the radius, width and effective refractive index n_{eff} of the ring. The ring can be regarded as resonator. The resonant wavelength λ_{res} is dependent on the circumference L and the effective refractive index n_{eff}, which can be expressed as

$$\lambda_{\mathrm{res}}=n_{\mathrm{eff}}L/N \tag{2}$$

where L is the circumference of the ring, N is the mode number that is a positive integer. As the widths of the air waveguide and the rings are $w=50$ nm, from Eqs. (1) and (2), it can be gotten the resonant wavelengths of the rings O_1, O_2, O_3, O_4 with radii of 85 nm, 105 nm, 125 nm and 140 nm are about 835 nm, 1 009 nm, 1 184 nm and 1 380 nm, respectively. By reason of resonance, the energy will be trapped in the ring when the incident wavelength reach the resonance wavelength of the ring and then coupled into the output port, thus leads to the wavelength demultiplexing function. Both the numerical simulation results and the resonance theory demonstrate that the different electromagnetic waves can be divided into different output ports of the wavelength demultiplexing structure.

To more comprehensive understand the property of the structure, the transmission characteristic with different parameters is investigated. When the subwavelength rings filled with different media, the transmission spectra of output ports are shown in Fig. 6. Figs. 6 (a) ~ (d) exhibit the transmission spectra of output port 1 ~ 4 with different refractive indexes of the ring. It can be seen that the refractive indexes of the filled medium mainly influence the resonant wavelength of the ring. The resonant wavelengths have red shift when the value of refractive indexes is increased.

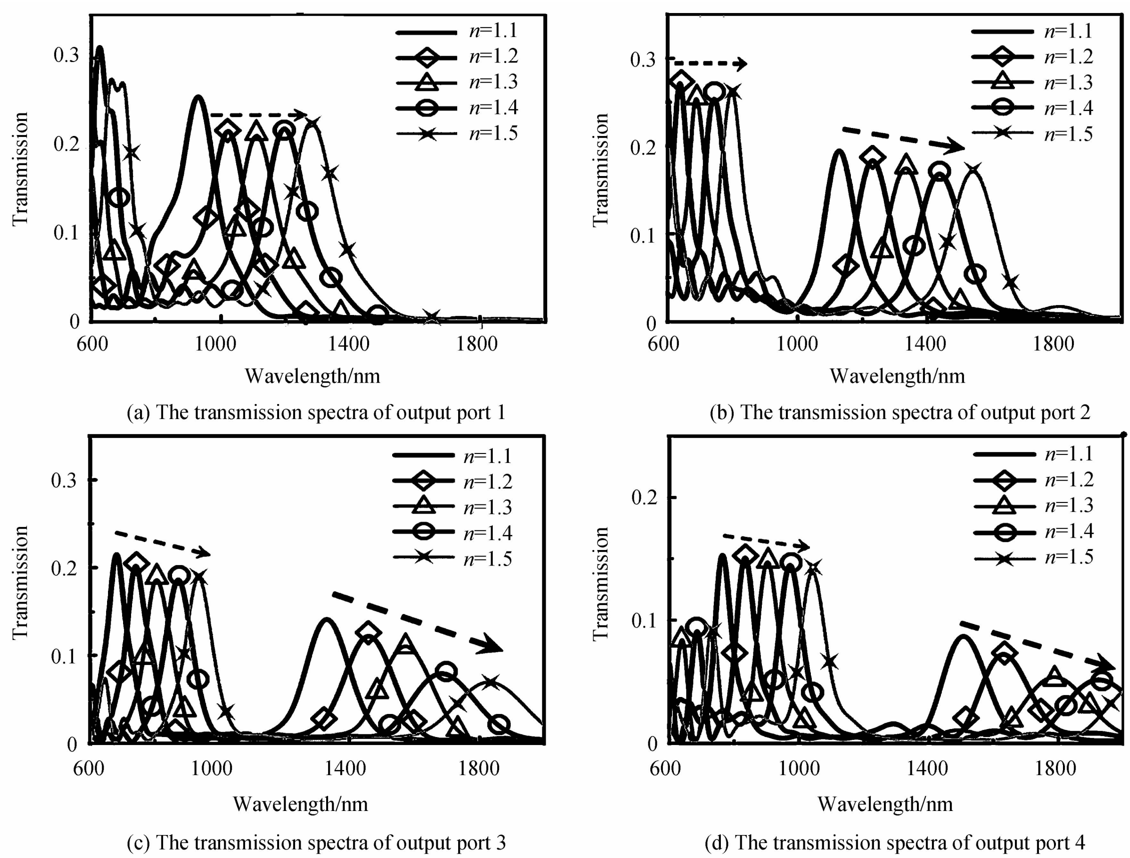
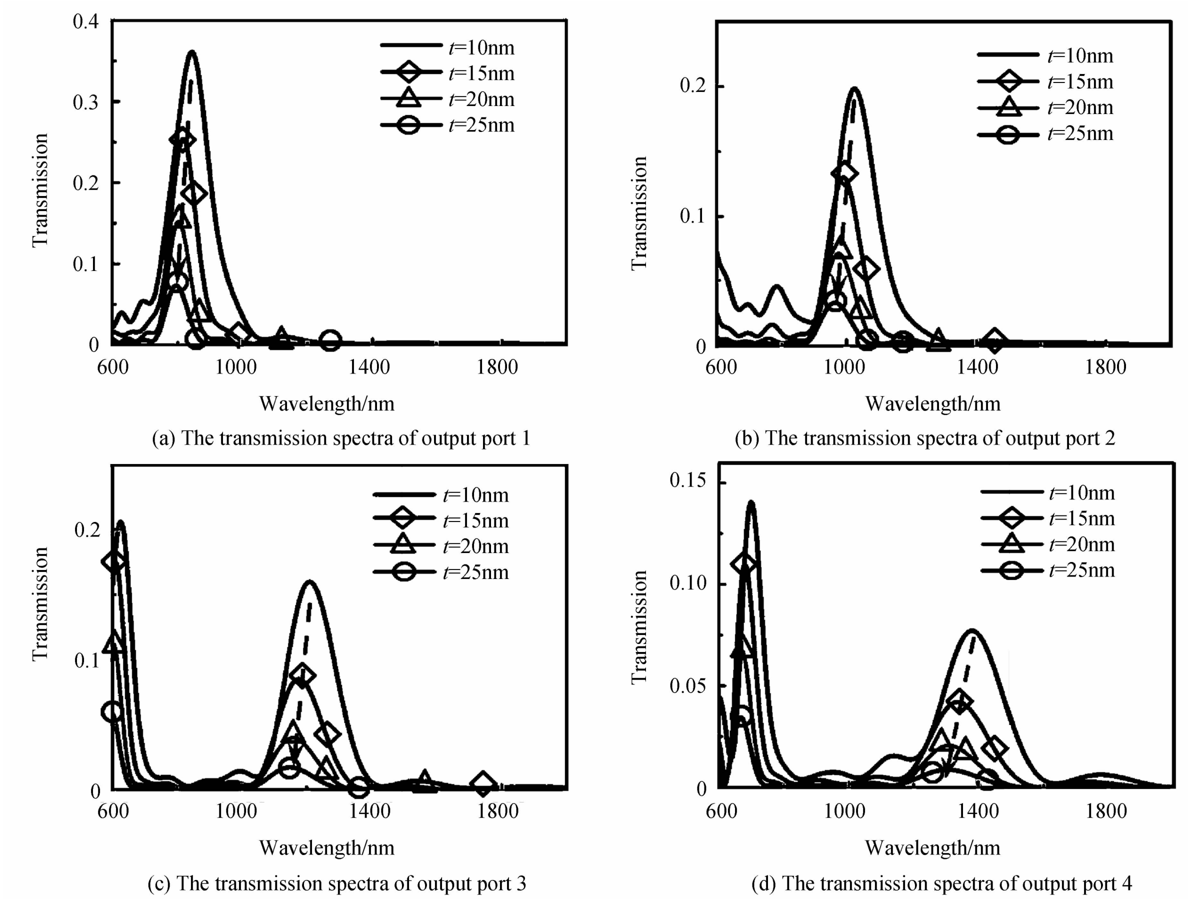


Fig. 6 The transmission spectra of output port 1 to port 4 with different refractive indexes of the ring

Fig. 7 shows the transmission spectra of the output ports with different coupled thicknesses t. It can be seen that the transmittance of the electromagnetic waves in the output ports is heavily influenced by the coupled thickness t. The transmittance of the waves in different output ports are reduced rapidly with increase of the thickness t. But, the resonant wavelength of the ring remains unchanged.



(a) The transmission spectra of output port 1

(b) The transmission spectra of output port 2

(c) The transmission spectra of output port 3

(d) The transmission spectra of output port 4

Fig. 7 The transmission spectra of output port 1 to port 4 with different coupled thicknesses

The resonance theory implies that the resonant wavelength is related to the radius of the ring. The resonant wavelengths of the proposed MIM waveguide are extracted with different radii of the ring, as shown in Fig. 8. It shows near linear relationship between the resonant wavelength and the radius.

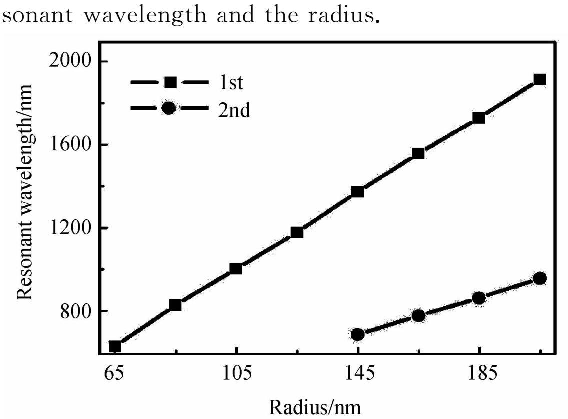


Fig. 8 The relationship between the resonant wavelength and radius of the subwavelength ring MIM waveguide

3 Conclusion

A multiple-ring shaped MIM waveguide structure with multi-output ports was proposed. The transmission characteristics were investigated by using FDTD method with PML absorbing boundary conditions. The results show that different wavelengths electromagnetic energy could be trapped in different rings and transmitted in the corresponding output port, thus can realize the wavelength demultiplexing function. According to the resonance theory, the resonance wavelength is dependent on the circumference and the effective refractive index of the ring, which can explain the demultiplexing phenomenon of the waveguide. Besides, the resonant wavelength has near linear relationship with the radius of the ring and has red shift with increase the value of the filled refractive index. The transmittance of electromagnetic waves in the output ports are heavily influenced by the coupled thickness. This structure may open up new avenues toward the development of demultiplexer.

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