Integrated tunable optofluidics filter based on the plasmonic structure with double side-coupled cavities*

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A novel method is presented to enhance the resonant transmission contrast ratio in metal-insulator-metal (MIM) side-coupled-cavity waveguide. The finite difference time domain (FDTD) method is used to simulate and study the optical properties of the filter based on double side-coupled cavities structure with optofluidics pump system (OPS). This system provides a flexible way to change wavelength in the optical filter. In the numerical simulation, the resonant wavelengths from 1000 nm to 1550 nm are analyzed. We find that the double side-coupled cavities structure with OPS has higher on-resonance transmittance and better wavelength selectivity than the single side-coupled cavity structure with OPS.

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Now many waveguide structures based on surface plasmon polaritons (SPPs) have been manufactured[1], such as the splitters[2], filters[3,4], Y-shaped combiners[5], U-shaped waveguides[6], couplers[7], reflectors[8,9] and Mach-Zehnder interferometers[10]. However, all the SPP devices above can't realize the high integration. How to actively control the optical signal in nanoscale device and to achieve the high integration is still a challenge. Nowadays, there is a very promising way to manipulate the output wavelength of the filter, i.e., optofluidics pump system (OPS). It can be flexible to realize the adjustment of wavelength and transmittance by using OPS. The optical filter based on OPS with simple configuration can be easily tuned in a broad band and can control the transmission characteristics by manipulating the fluid filled in the cavity[11], for example, tunable attenuators[12,13], tunable interferometers[14] and tunable filters[15,16]. The single side-coupled cavity structure with OPS has been presented[11]. But owing to the limitation and the intrinsic loss of the metal in this structure, it can't get a good filtering effect, which limits its further application in the nanoscale optical device.

In this paper, the double side-coupled cavities structure with OPS is constructed and theoretically investigated, which has higher on-resonance transmission contrast ratio than the single side-coupled cavity structure with OPS. The dependence of the filter wavelength of the structure on liquid pumped in the two rectangular cavities is analyzed. The finite difference time domain (FDTD) method with perfectly matched layer (PML) absorbing boundary condition is used in numerical simulations to demonstrate the theoretical results.

The single side-coupled cavity structure with OPS illustrated in Fig.1 is simply composed of two slits, i.e., the metal-insulator-metal (MIM) SPP waveguide and a cavity serving as resonator for SPP wave. The two ends of the cavity are connected with the fluid channels which are linked with OPS. We discuss the characteristics of the single side-coupled cavity structure with OPS, where the length of cavity is L=400 nm, the widths of waveguide and cavity are equal, i.e., W=100 nm, the gap between the cavity and the waveguide is G=28 nm, and L_f is the length of the fluid filled in the cavity. The circumambience of the structure is silver. Owing to the advanced fluid processing technology, the fluid injected into the cavity can be controlled by the OPS[17-22]. Such a single side-coupled cavity structure with OPS supporting a resonant mode with frequency of ω_0 can be described analytically by using the coupled-mode theory[23], and the transmission wavelength λ_m of the system is determined by[11]

$$\lambda_m = \frac{2L_f(n_1 - n_2) + 2Ln_2}{m - \varphi_{ref}/\pi}, \tag{1}$$

where n_1 is the refractive index of fluid, and n_2 is the refractive index of air. Defining n_{eff} as the real part of the effective refractive index in the resonant cavity, it can be decided by[11]

$$n_{eff} = \frac{\lambda_m(m - \varphi_{ref}/\pi)}{2L}. \tag{2}$$

From Eqs.(1) and (2), we can deduce n_{eff} as

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$$n_{\text{eff}} = \frac{[n_1 L_{\text{f}} + n_2 (L - L_{\text{f}})]}{L} . \tag{3}$$

From Eqs.(1)–(3), we can conclude that the transmission wavelength λ_m is related to n_{eff} and L_{f}, and the volume of fluid pumped in the short waveguide segment can be altered by OPS. It means that the effective refractive index can be changed. The resonant wavelength of the structure changes with the variation of the kind of fluid pumped into the cavity, so that we can achieve the adjustable plasmonic optical filter. The FDTD method is used for simulation, and the grid size in x and z directions is chosen to be 5 nm×5 nm. Two power monitors are set at the positions of M_1 and M_2 to detect the incident power P_{in} and the transmitted power P_{tr}, respectively. The transmittance of the structure is defined as $T=P_{\text{tr}}/P_{\text{in}}$.

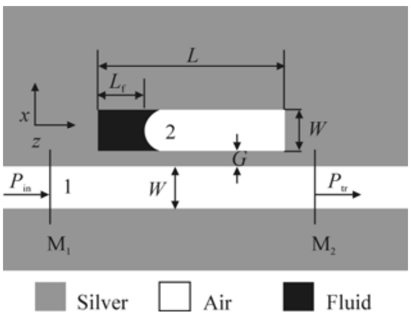
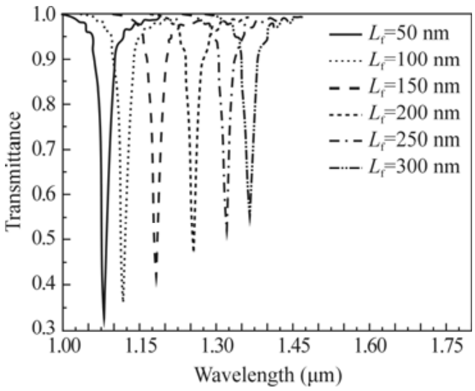


Fig.1 Schematic diagram of the single side-coupled cavity structure with OPS, where 1 is MIM SPP waveguide, and 2 is the cavity

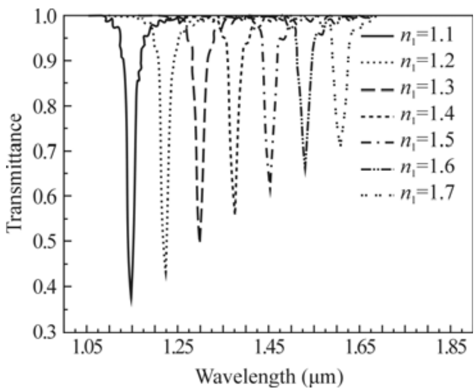
As shown in Fig.2(a), when n_1 is fixed, the shift of the resonance wavelength is 284 nm as the fluid column length changes from 50 nm to 300 nm. We can get different wavelength λ_m by changing the length of fluid pumped in the cavity. Fig.2(b) indicates that a red shift occurs in the transmission spectra with the increase of n_1 when L_{f} is fixed.

From the discussions above, we can infer that the output wavelength can be dynamically tuned through the manipulation of OPS. But the light transmittance is too high, so it is not the best choice to be a filter.

As shown in Fig.3(a), the double side-coupled cavities structure with OPS is proposed. In this structure, the two



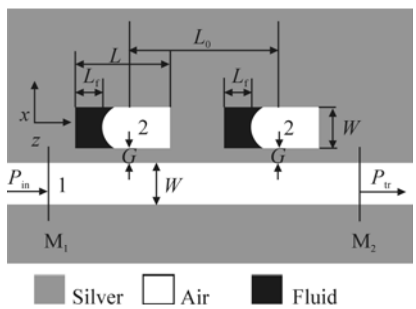
(a)



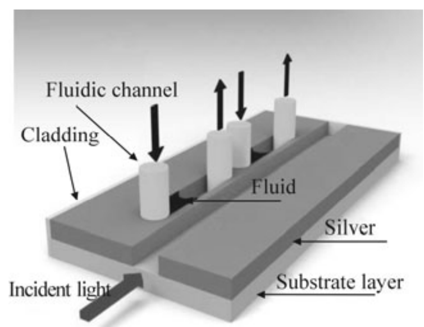
(b)

Fig.2 The transmission spectra of the single side-coupled cavity structures (a) for water with different fluid column lengths in the cavity and (b) for fluids with different n_1 in the cavity and L_f =250 nm

cavities are the same and parallel to each other. An OPS is integrated with the MIM coupler, and multi-wavelength output can be realized without changing the parameter of the coupler. The values of L, W and G are the same as those in the single side-coupled cavity structure with OPS. L_0 stands for the distance between the centers of two cavities. In order to obtain the same resonant frequency, the length of L_0 is set to be 600 nm. The distance can get the minimum direct coupling between the cavities[24]. Fig.3(b) shows the schematic diagram of the tunable OPS.



(a)



(b)

Fig.3 (a) Basic two-dimensional structure map of the SPP coupled-cavity filter; (b) Basic three-dimensional structure map of SPP side-coupled-cavity filter with the fluidic channel

Because the two cavities are the same, the real parts of the effective indices of the two cavities are equal, which can be calculated by Eq.(3). The temporal coupled-mode theory[23] can be used to analyze the response of the double side-coupled cavities structure with OPS. The minimum resonance of the transmission can be indicated as

$$T_{\min}=\frac{(1/\tau_0)^4}{(1/\tau_0+1/\tau_e)^4+(1/\tau_e)^2-2\cos(2\rho)(1/\tau_0+1/\tau_e)^2}\ . \quad (4)$$

If the propagation loss in the MIM waveguide between two cavities is neglected, the minimum of the on-resonance transmission appears when $\rho=(n+1/2)\pi$. To produce the resonance condition, the standing wave condition must be satisfied, namely

$$\Delta\rho=K(\omega)\cdot L+\varphi_r=m\cdot 2\pi\ , \quad (5)$$

$$K(\omega)=2\pi n_{\text{eff}}/\lambda\ . \quad (6)$$

Substituting Eqs.(5) and (6) into Eq.(4), we can get

$$1/T_{\min}=\frac{(1/\tau_0+1/\tau_e)^4+(1/\tau_e)^2}{(1/\tau_0)^4}-\frac{2\cos(4\pi Ln_{\text{eff}}/\lambda+2\varphi_r)(1/\tau_0+1/\tau_e)^2}{(1/\tau_0)^4}\ , \quad (7)$$

where $1/\tau_0$ is the decay rate of the intrinsic loss, $K(\omega)$ is the angular wavenumber, $1/\tau_e$ is the decay rate due to the power escaping through the waveguide, φ_r is the phase shift of the reflection, and m is an integer. At this point, both $1/\tau_0$ and $1/\tau_e$ are assumed to be the dispersion loss. From Eq.(7), we can know that the transmittance is determined by the real part of the effective refraction index of the fluid in resonant cavity. One can change the volume and the kind of the fluid pumped in the short waveguide segment to realize the change of the effective refractive index. So we can achieve a tunable wavelength by operating the OPS.

The transmission spectra of the double side-coupled cavities structures for water and oil are shown in Fig.4(a) and (b). It can be seen from Fig.4(c) that the transmission wavelength is increased linearly with the increase of the fluid column length (L_f) in the cavity. When L_f is equal to 50 nm, the effective index n_{eff} of the cavity with different fluids can be calculated by solving the Eq.(3) as 1.0412. Submitting n_{eff}=1.0412 and T=0.0688 into Eq.(7), λ_m is about 1081 nm. Other transmission wavelengths also can be calculated by using Eq.(7). When L_f =50 nm and fluid is water, the transmittance of the single side-coupled cavity structure with OPS is 0.326 obtained from Fig.2(a), and the transmittance of the double side-coupled cavities structure with OPS is 0.069. It proves that the double side-coupled cavities structure with OPS has better transmittance than the single side-coupled cavity structure with OPS.

In the following simulations, L_f is fixed at 150 nm, fluids with different refractive indices are pumped into the cavity, and the geometric dimension of the structure is not changed. The results of the double side-coupled cavities structures with L_f=150 nm and 250 nm are shown in Fig.5. We can learn that the resonance wavelength increases linearly with the increase of refractive index n_1 of the fluid in the cavity as shown in Fig.5(c). At the same time, it can be seen that $d\lambda_m/dn_1$ is about 0.33 when L_f is equal to 150 nm, and $d\lambda_m/dn_1$ changes to be close to 0.773 when L_f increases to 250 nm. Therefore, the manipulation of structure with large scale can be realized by using fluid with higher refractive index and longer fluid column. Compared with single side-coupled cavity structure with OPS under the same fluid column length and the same refractive index, the double side-coupled cavities structure with OPS has better device performance.

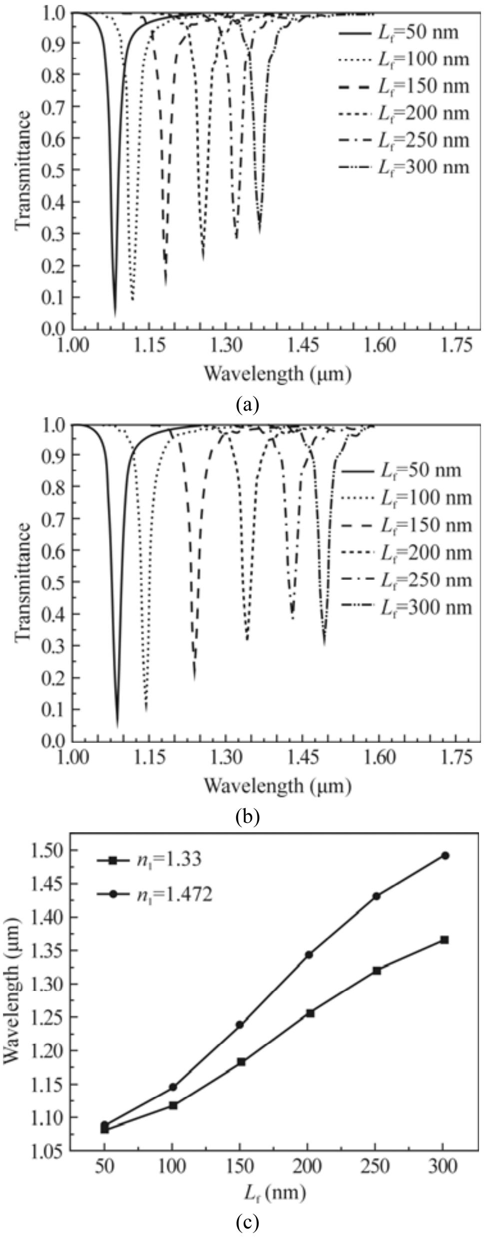


Fig.4 The transmission spectra of the double side-coupled cavities structures for (a) water and (b) oil with different fluid column lengths in the cavity; (c) Resonance wavelength of the transmission spectrum versus the fluid column length in the cavity

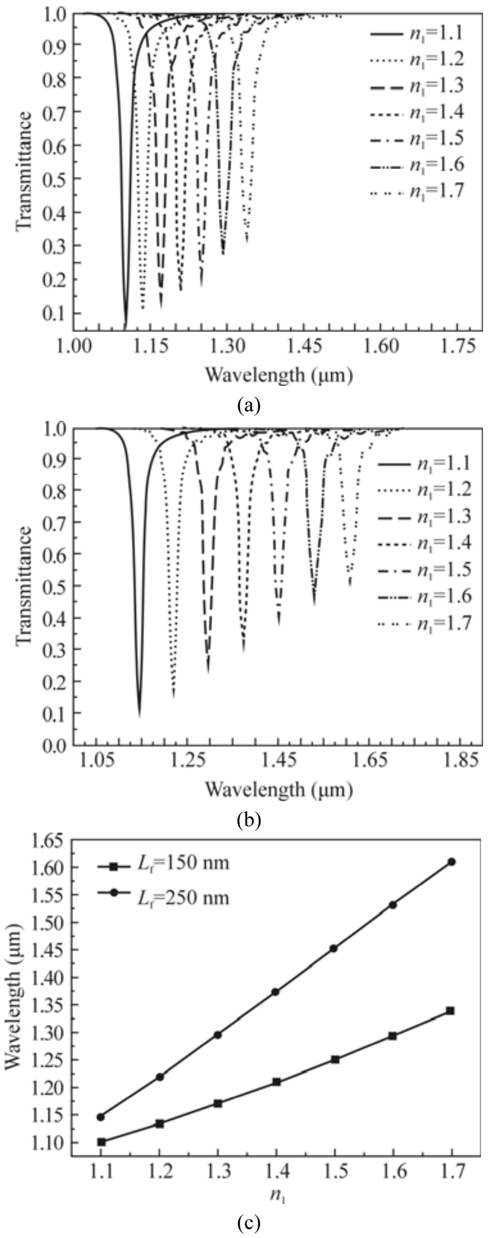


Fig.5 The transmission spectra of the double side-coupled cavities structures for the fluids with different n_1 in the cavity when (a) L_f =150 nm and (b) L_f=250 nm; (c) Resonance wavelength of the transmission spectrum versus the refractive index of the fluid in the cavity

In this paper, the integrated tunable optofluidics filter based on the double side-coupled cavities plasmonic structure is presented. In the numerical simulation, OPS is used to change the fluid column length and the refractive index of fluid in the side cavity, so that we can get different resonant wavelengths, and then a tunable optical filter can be realized. The double side-coupled cavities structure with OPS has better transmission contrast ratio and better wavelength selectivity than the single side-coupled cavity structure with OPS. Furthermore, the design principle can be easily applied to construct nano-scale high-density photonic integration circuits.

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