High-Efficiency Nanoplasmonic Dual-Band Band-Stop Filters Using Step Impedance Resonators

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***Abstract*—This article presents dual-band stop filters using quarter-wavelength step-impedance resonators (SIRs)in subwavelength MIM structures, operating at 186.67 THz and 227.63 THz. Full-wave simulations analyze variations in transmission and reflection coefficients to validate concurrent filtering performance at the targeted optical frequency bands.**

***Index Terms*—Nanoplasmonic, SIRs, Band-Stop, PICs**

I. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves confined to metal–dielectric interfaces, arising from the interaction between incident photons and oscillations of conduction electrons. These waves exhibit exponential field decay perpendicular to the interface and enable subwavelength confinement beyond the diffraction limit. Unlike conventional optical waveguides that carry only photonic signals, SPPs support the propagation of both optical and electronic signals, making them well-suited for nanoscale integration and high-density photonic integrated circuits (PICs). The slow-wave nature of SPPs leads to shorter wavelengths, reduced phase velocity, and higher surface impedance compared to waves in equivalent dielectric media. These characteristics allow SPP-guiding structures to be effectively modeled using transverse electromagnetic (TEM) equivalent transmission line theory.

Various nanoplasmonic waveguiding structures, such as insulator-metal-insulator (IMI), MIM waveguides, and nanowires, have been explored for PICs. Among them, MIM structures offer superior subwavelength confinement and light localization. Numerous SPP-based MIM devices, including filters [1] and diplexers [2], have been demonstrated. However, these components typically operate within a dual frequency band, primarily exhibiting band-pass characteristics.

Recently, bandpass filters operating under odd-mode conditions ($R_Z = Z_2/Z_1 < 1$), along with a diplexer designed for PICs, have been reported in [3] and [4]. This work presents the design of a concurrent dual-band bandstop filter based on even-mode conditions ($R_Z = Z_2/Z_1 > 1$), where the field distribution exhibits even-mode symmetry. The proposed filters are implemented using planar plasmonic MIM waveguides. The transmission line characteristics, dual-band filtering response, and band-stop behavior of SIRs are analyzed. Full-wave simulations using CST Microwave Studio validate the proposed design.

II. Design and Analysis of Band Stop Filters

Fig.1 illustrates the SIR and its equivalent circuit, implemented using a plasmonic MIM waveguide with a single centrally position slit. Fig.2 shows the geometry of the proposed band-stop filter. Silica (SiO_2) is used as the dielectric medium with a relative permittivity of $\varepsilon_r = 2.50$, while the frequency-dependent permittivity of silver follows the Drude model [5]. The narrow waveguide supports the fundamental transverse magnetic (TM) mode due to its subwavelength width. SPPs entering the input port are partially reflected and coupled into the resonant cavity, where they propagate along the metal–dielectric interfaces and form standing waves that couple to the output port. The resonance conditions for the fundamental and spurious frequencies are detailed in [6].

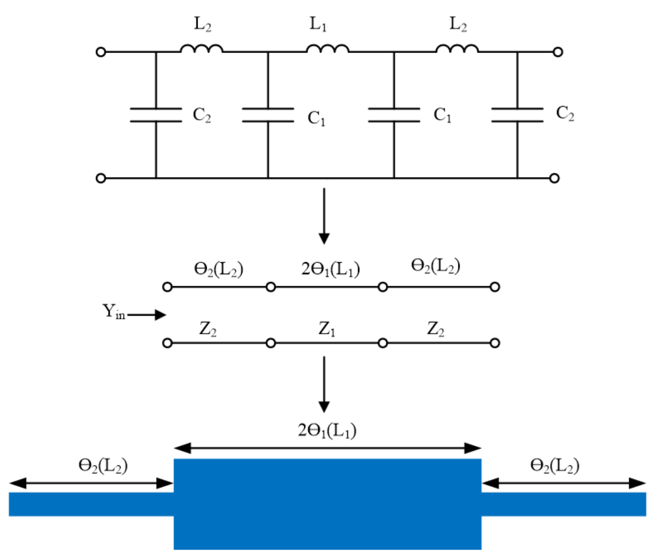

Fig. 1. Geometry of the quarter-wavelength SIR and its equivalent circuit.

In each plasmonic SIR, resonance occurs in either the even or odd mode. The odd mode represents the fundamental resonance, whereas the even mode supports the first and higher-order resonances. The resonance conditions are given by:

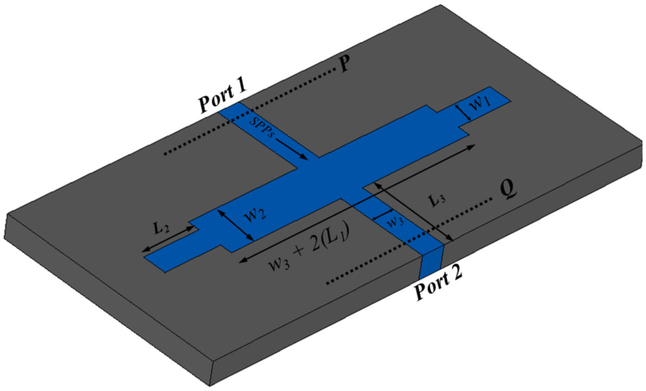

Fig. 2. Schematic of the plasmonic Band Stop Filter

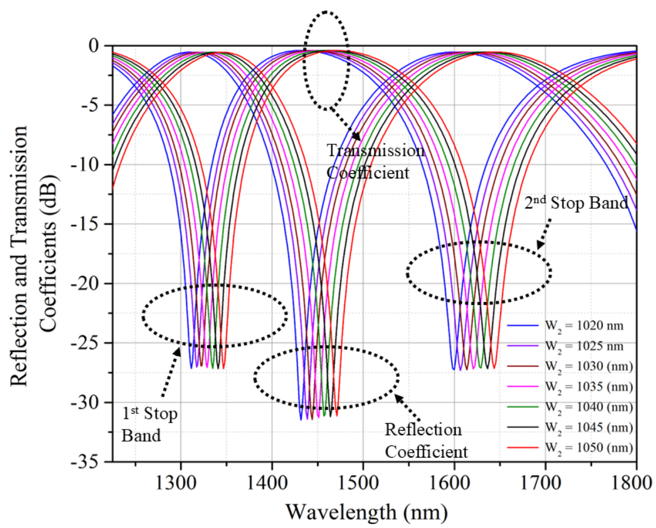

Fig. 3. Transmission and reflection coefficients of the band stop filter

$$\tan\theta_1 = R_Z \cot\theta_2 \qquad \text{(odd-mode)} \qquad (1)$$

$$\tan\theta_2 = -R_Z \tan\theta_1 \qquad \text{(even-mode)} \qquad (2)$$

$$R_Z = \frac{Z_2}{Z_1} = \tan\theta_1 \tan\theta_2 \qquad \text{(impedance ratio)} \qquad (3)$$

The relationship between fundamental and spurious resonance frequencies for the special case $\theta_1 = \theta_3 = \theta_0$ is given in [1]. In the simulation, power monitors P and Q are placed equidistant from the center of the MIM SIR to measure the input and output power levels. A grid size of 5 nm $\times$ 5 nm is used along the x and y directions. The fundamental TM mode is excited from the left, propagating rightward. Only the fundamental TM mode can propagate, as the waveguide width is subwavelength.

$$\lambda \frac{f_{S1}}{f_0} = \frac{\pi}{2\tan^{-1}\sqrt{R_Z}} \qquad (4)$$

$$\lambda \frac{f_{S3}}{f_0} = \frac{\pi}{\tan^{-1}\sqrt{R_Z}} \qquad (5)$$

where f_0, f_{S1}, and f_{S3} represent the center, first spurious, and second spurious frequencies, respectively.

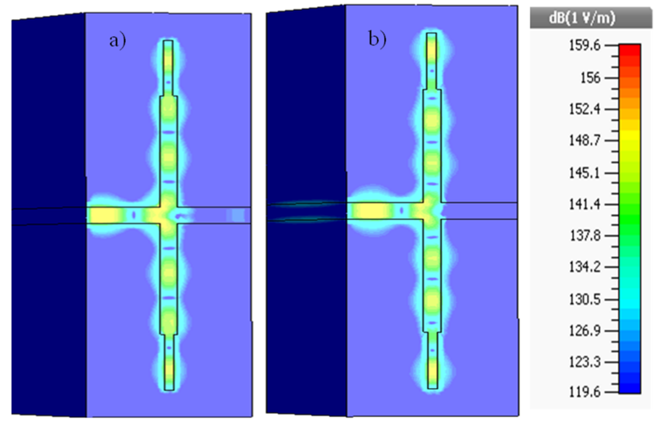

Fig. 4. Field distribution at wavelengths: (a) 1606 nm and (b) 1317 nm.

The dual-band filter is designed and simulated with fixed dimensions: $w_1 = 62$ nm, $w_2 = 100$ nm, $w_3 = 30$ nm, satisfying the condition $w_3 + 2L_1 = 2250$ nm, and lengths $L_1 = 1050$ nm, $L_2 = 525$ nm, and $L_3 = 500$ nm. The transmission coefficients of the proposed band-stop filter are shown in Fig. 3. Based on Eq. (1), resonance occurs at $R_Z = 5.9$. The first stopband peak appears at the fundamental frequency $f_0 = 186.67$ THz (1607 nm), while the second peak occurs at the first spurious frequency $f_{S1} = 227.63$ THz (1317 nm) for $\theta_1 = \theta_2 = \theta_0$. However, due to unequal electrical lengths θ_1 and θ_2, the second peak shifts slightly to 1320 nm, as shown in Fig.3. The parametric analysis demonstrates that varying L_1 has a more pronounced effect on transmission than changes in w_2, indicating its greater influence on the resonance behavior. Fig. 4 shows the field distribution at 1606 nm and 1317 nm wavelengths.

Conclusion

Dual-band band-stop filters have been designed and analyzed using SIR structures based on MIM waveguide structures. The proposed filters operate efficiently at optical frequencies of 186.67 THz and 227.63 THz, achieving suppression levels greater than 30 dB. These findings support advanced design approaches for nanoscale PICs based on SPPs.

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