Miniaturized Dual-Band Filters Utilizing Square Ring Resonators with Coupling Gaps

[1, 2] Kola Thirupathaiah, [2] Montasir Qasymeh
[1]Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education Foundation, Hyderabad-500075, India
[2] Department of Electrical Engineering, Abu Dhabi University, Abu Dhabi, UAE
kola.jntu@gmail.com, montasir.qasymeh@adu.ac.ae

***Abstract*—This article explores the square ring resonators (SRRs) in a MIM waveguide for dual-band filtering. Full-wave simulations show dual-band behavior with peaks at O and L optical frequency bands. While losses increase with SRR gaps, all designs exhibit bandpass characteristics, enabling miniaturized photonic devices.**

***Index Terms*—Nanoplasmonic, SRRs, Band Pass, PICs**

I. Introduction

This paper explores coupling gap based nanoplasmonic square ring resonators (SRRs) in MIM waveguides for improved performance compared to linear resonators [1]. Slits are introduced to facilitate integration with electronic devices, offering functionalities like optical excitation and switching. The research suggests that strategically placed slits minimally affect the mode structure, making them suitable for numerical analysis using coupled mode theory (CMT) [2]. Additionally, recent work by Huwang demonstrates the creation of multiple stop bands by introducing a narrow gap in the SRR, allowing control over central and stopband frequencies [3].

This work investigates the dual-band nature of SRRs transmitted modes at optical frequencies (O & L bands) using nanoscale plasmonic MIM waveguide filters. Focusing on filtering and transmission characteristics, full-wave simulations reveal that resonant modes can be adjusted by altering the SRR radius and slit separations. These designs reduce filter dimensions and enhance optical applications in photonic integrated circuits. Numerical results were obtained using the CST Microwave Studio Suite.

II. Design and Analysis Of SRR Filters

Fig. 1, 3, and 5 depict ring resonators with coupling gaps, using plasmonic MIM waveguides and a double-slit configuration in the center. Silica (SiO_2) serves as the dielectric ($\epsilon_{SiO_2} = 2.50$), while silver's frequency-dependent dielectric constant follows the Drude model [4]. The narrow waveguide supports the fundamental TM mode due to its width relative to the operating wavelength. Surface plasmon polaritons (SPPs) entering the input port reflect or couple into the cavity. Waves propagate along interfaces, forming standing waves that couple to the output port. Resonance conditions for the rectangular ring are detailed in [5].

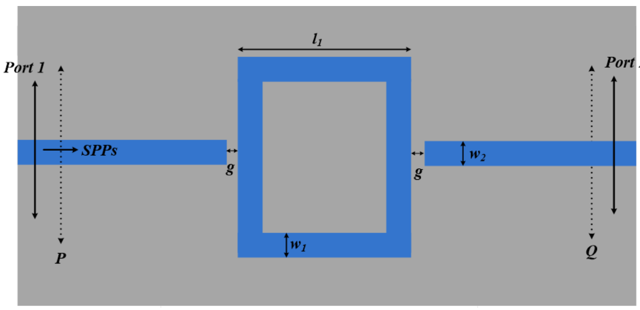

Fig. 1. Geometry of the square ring resonator with $l_1 = 976$ nm, $w_1 = 90$ nm, $w_2 = 80$ nm, and $g = 3$ nm.

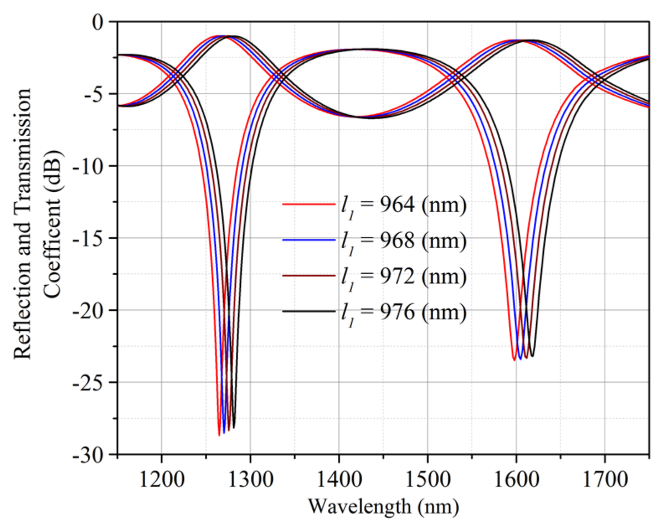

Fig. 2. Variation of reflection and transmission coefficients with wavelength as a function of length (l_1).

$$\lambda_m = \frac{\lambda_0}{\left(\frac{\beta_g}{\beta_0}\right)} = \frac{l_1 + l_2}{m} \tag{1}$$

where $m = 0, 1, 2, 3, \ldots$, and $\frac{\beta_g}{\beta_0}$ is the normalized propagation constant and λ_0 is the fundamental wavelength.

The transmission characteristics of MIM waveguide-based square ring resonators were simulated using CST Microwave Studio. For resonators without slits or gaps, the waveguide and cavity widths were fixed, resulting in a total length $l = 2(l_1 + l_2) = 3904$ nm, where $l_1 = l_2 = 976$ nm as

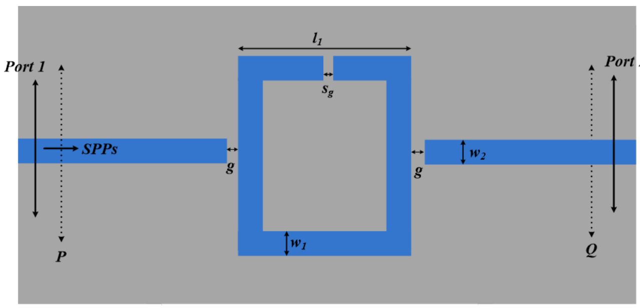

Fig. 3. Geometry of the square ring resonator with single slit (gap) perturbations of $l_1 = 780$ nm, $w_1 = 90$ nm, $w_2 = 120$ nm, $g = 6$ nm, and $s_g = 4$ nm.

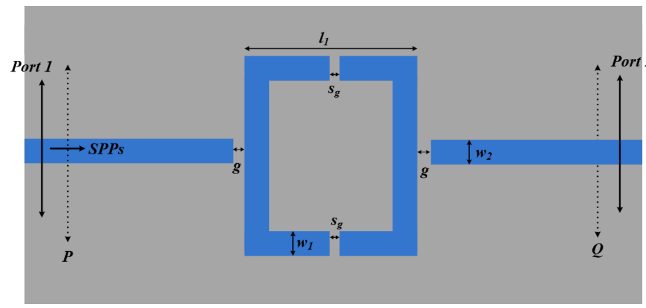

Fig. 5. Geometry of the square ring resonator with two slit (gap) perturbations of $l_1 = 776$ nm, $w_1 = 90$ nm, $w_2 = 120$ nm, $g = 5$ nm, and $s_g = 2$ nm.

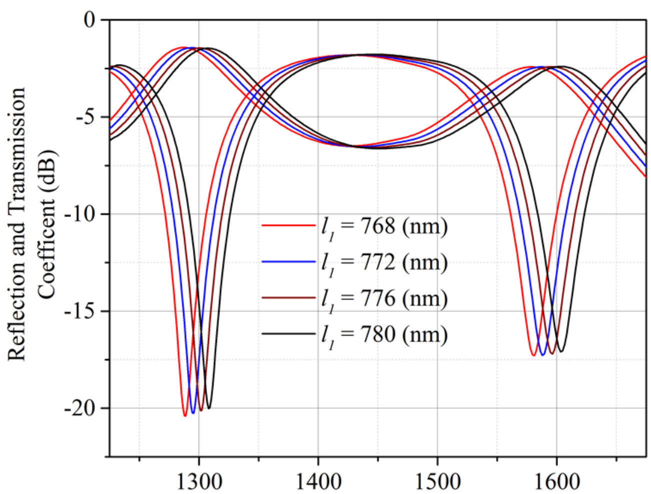

Fig. 4. Variation of reflection and transmission coefficients with wavelength as a function of length (l_1).

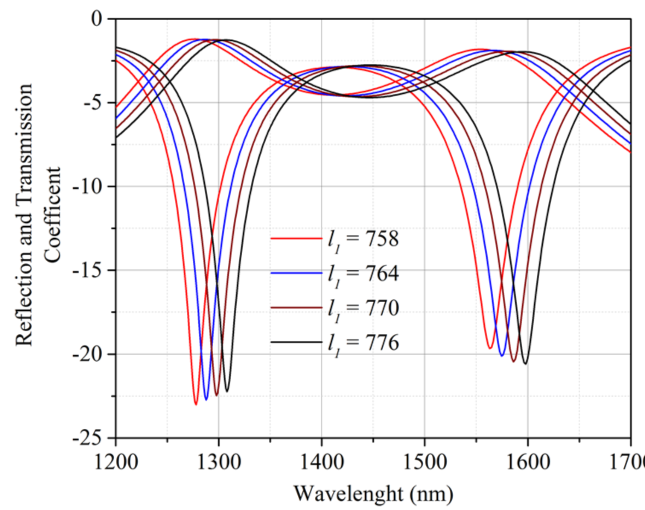

Fig. 6. Variation of reflection and transmission coefficients with wavelength as a function of length (l_1).

depicted in Fig. 1. Figure 2 shows the transmission spectra of the square ring resonator as a function of wavelength for wideband light. The first resonant peak occurred at 1300 nm and the second at 1600 nm. Increasing the resonator length shifted the transmission spectrum to the right, resulting in resonant wavelengths shifting from 1265 nm to 1275 nm for the first peak and from 1565 nm to 1600 nm for the second, with transmission losses of 28 dB and 23 dB, respectively.

For resonators with a single slit, the total length was $l = 2(l_1 + l_2) = 3120$ nm, with $l_1 = l_2 = 780$ nm as shown in Figure 3. Figure 4 illustrates the transmission spectra variation with slit width S_g as a function of wavelength for wideband light. The resonant peaks were observed at 1300 nm and 1600 nm wavelengths, with transmission losses of 20 dB and 17.5 dB, respectively. Increasing the resonator length shifted the resonant wavelengths from 1290 nm to 1307 nm for the first peak and from 1550 nm to 1603 nm for the second.

For resonators with two slits or gaps, the total length was $l = 2(l_1 + l_2) = 3104$ nm, where $l_1 = l_2 = 776$ nm as depicted in Fig. 5. Figure 6 presents the transmission spectra variation with single slit width S_g as a function of wavelength for wideband light. The resonant peaks occurred at 1300 nm and 1600 nm wavelengths, with transmission losses of 22 dB and 20 dB, respectively. Increasing the resonator length shifted the resonant wavelengths from 1275 nm to 1307 nm for the first peak and from 1560 nm to 1603 nm for the second.

Conclusion

Square ring resonators with varying numbers of slits or gaps were analyzed using CST Microwave Studio. Increased slit or gap numbers correlated with higher transmission losses. Despite this, all resonators exhibited dual-band behavior at 1300 nm and 1600 nm, with band-pass filter characteristics. These designs promise compact filter dimensions and significant potential in silicon Photonic Integrated Circuits (PICs).

References

[1] M. Zavvari, M. Taleb Hesami Azar, and A. Arashmehr, “Tunable band-stop plasmonic filter based on square ring resonators in a metal-insulator-metal structure,” J. Mod. Opt., vol. 64, no. 20, pp. 2221–2227, July 2017.
[2] K. Thirupathaiah and M. Qasymeh, ”Optical Ultra-Wideband Nano-Plasmonic Bandpass Filter Based on Gap-Coupled Square Ring Resonators,” in IEEE Access, vol. 11, pp. 106095-106102, 2023.
[3] K. Thirupathaiah, B. Iyer, N. P. Pathak, and V. Rastogi, ”Concurrent dualband diplexer for nanoscale wireless links,” IEEE Photon. Technol. Lett., vol. 26, no. 18, pp. 1832–1835, Sep. 2014.
[4] Oulton, Rupert F., Volker J. Sorger, D. A. Genov, D. F. P. Pile, and X. Zhang. ”A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation.” nature photonics, vol.2, no. 8, pp. 496-500, July 2008.
[5] Kai Chang, et. al, ”Slow-wave bandpass filters using ring or stepped-impedance hairpin resonators,” IEEE Trans. Micro. Theo. and Techn.,, vol. 50, no. 7, pp. 1795-1800, July 2002.