Design of Concurrent Dual-Band Band Pass Filter using Hybrid Metal insulator Metal for Nanoscale Applications

Surendra Kumar Bitra and Sridhar M
Department of ECE, KLEF, Vaddeswaram, Andhra Pradesh, India

Abstract. In this paper, investigation on Hybrid Metal Insulator Metal (HMIM) plasmonic waveguide (PWG) filters for dual-band applications. The filters are designed using circular ring resonator (CRR) and CRR with single as well as dual slits. The filters are connected using coupled line feed. The dual-band Band Pass Filter (BPF) characteristics can be realized by varying radius (r) and gap (g) between the feed and ring resonator. The proposed CRRs are operated at THz frequencies. The filters are designed and simulated using commercially available CST studio suite software under Perfect Matched Layer (PML) boundary conditions by keeping 5 nm x 5 nm mesh size. The transmission and reflection characteristics of the filters are explained by the resonance conditions, which agrees with theoretical calculations. The proposed work is best suitable for the plasmonic integrated optical circuits for nanoscale applications.

Keywords: HMIM Waveguide, CRR, Single slit and Dual slit.

1. Introduction

The waveguide components like splitters, couplers, bends, ring resonators and antennas are widely used in optical communication systems. These components used for splitting, bending, filtering and radiation of optical signals in the communication system. Various components used for optical communications are studied in [1-10]. The conventional photonic devices are very tiny and not best suitable for IC designing. Due to nano meter range scaled down components of plasmonic structures, feasible to best solution for this problem [1-3]. Various plasmonic waveguides (PWG) proposed with applications in literature [11-13]. Ring resonator with asymmetric PWG for sensing application is proposed by Zou et al. A dielectric loaded PWG for splitter application is designed and analyzed by H-S chu et al. 3D plasmon power splitter was proposed by Dastmalchi et al for integrated circuits. A long range PWG is used for designing a direction coupler is proposed by A. Boltasseva [14]. The designed components are very large size; hence these are producing ohmic losses in integrated circuit design for practical applications [15]. The performance of these components is degraded compare with the conventional photonic components. Hybrid PWGs are possible solution for overcoming these limitations. Hybrid PWG support hybrid modes combination of plasmonic as well as dielectric modes. Several Hybrid PWG are designed and analyzed in the literature [16-18].

A Hybrid Plasmonic directional coupler designed with low loss for broad band applications by Alam et al [16]. HMIM based directional coupler designed and analyzed [19]. Most of the work reported Hybrid PWG applications are three-layer structures like Hybrid Metal Insulator (HMI). The HMI based components are suffers with performance in terms of confinement factor and propagation length. Hence,
these waveguides are not satisfactory solution for integrated circuits. The HMIM and Hybrid insulator metal insulator (HIMI) waveguide and components are designed and analyzed in [20-25] for better confinement and good propagation length. Hence in this work we designed and analyzed the HMIM based CRR for dual band BPF applications.

In this paper, HMIM based CRR and CRR with slits using coupled line feeding is designed and analyzed. The proposed dual band BPF is possible for fabricate on semiconductor fabrication procedure techniques. The layers are deposited one by one using e-beam lithography processing.

The paper organization as follows, section 2 describes the HMIM waveguide based CRR for dual band operation. The CRR with single and dual slits using HMIM waveguide are designed and analyzed in section 3 and 4 respectively. Finally, the paper ends with the suitable conclusion.

2. Dual-Band Band Pass Filter (BPF) Design using Circular Ring Resonator (CRR)

The ring resonator filters are essential components in the modern communication systems, with applications like switches, wavelength division multiplexing, tunable filters, add-drop filters, optical delays and phase modulators etc [1-8]. Though these applications can also execute by Bragg grating and tooth shaped filters also. But these are suffering with a drawback of larger length and smaller foot print area respectively, these are producing high bandwidths for filtering applications. The HMIM plasmonic ring resonators are giving high extinction ratio and spectral range. The ring resonators are having high coupling efficiency and less fabrication sensitivity, it is the main motivation for this work.

The HMIM waveguide characteristics are taken from P. sharma et al. The figure 1(a) shows the proposed HMIM based CRR with coupled line feed structure and their equivalent diagram is represented in figure 1(b). The optimized design parameters are L1 = 200 nm, W1 = 50 nm, d = 50 nm, g = 2nm and R = 596 nm. For describing the functionality of the proposed structure, the incident EM field is launched to the input port. The output port resonates at specific wavelengths. In this research, at resonance wavelengths of output port, transmission and field distribution spectra are achieved. For improving the functionality of the system, effects of radius of waveguide on the peak value of transmission spectrum are also investigated and analyzed. All the simulations are carried out using CST studio suite and the mesh size is considered for simulation is 5 nm x 5nm under the PML boundary conditions.

The simulated characteristics of CRR are represented in figure 2. The reflection and transmission characteristics of the CRR by varying the radius (R) and gap (g) are shown in figure 2 (a) and (b) respectively. The figure 2(a) shows the CRR varying with R from 592 nm to 608 nm with a step size of 4 nm. The optimized radius is 596 nm with operating bands of 1300 nm (230.79 THz) and 1600 nm (186.95 THz) respectively. the figure 2(b) represented the CRR by varying the g from 2 nm to 6 nm.
with a step size of 2 nm. The optimized dimensions of the g are 2 nm. The simulated results show that the proposed CRR is operated in dual-band BPF characteristics and operated in 1300 nm and 1600 nm simultaneously with bandwidth of 43.80 nm and 64.127 nm respectively.

![Reflection and Transmission Coefficients](image)

(a) Wavelength in nm

(b) Wavelength in nm

Figure 2. Simulation results of CRR varying parameter of (a) radius (R) (b) gap (g)

The figure 3 shows the e-field distribution of the CRR at 1300 nm and 1600 nm respectively. The figures show that more energy confinement in the metal insulator regions of the HMIM waveguide.

![Field distributions of CRR at 1300 nm](image)

(a) 1300 nm (230.79 THz)

(b) 1600 nm (186.95 THz)

Figure 3. Field distributions of CRR at (a) 1300 nm (230.79 THz) and (b) 1600 nm (186.95 THz)

3. Design of CRR using single slit

A single slit with a gap of (g1) is included in the CRR and produces the proposed single slit CRR represented in figure 4 (a). The figure 4(b) shows the equivalent circuit for figure 4(a). The capacitance effect is inserted in the CRR for enhancing the bandwidth. The design parameters are used for CRR with single slit is L1=200 nm, W1 =55 nm, g = 2 nm, g1 = 4 nm, r = 602 nm and d = 50 nm.
Figure 4. (a) CRR structure using single slit (b) Equivalent lumped model of CRR using single slit

The simulated results of reflection coefficient and transmission coefficient of the CRR with single slit by varying the radius (R) and gap of the slit (g1) is represented in figure 5 (a) and (b). The optimized value of R is 602 nm and g1 is 2 nm. The simulated results of the CRR using single slit operated in two wavelengths of 1273.6 nm (235.74 THz) and 1598.3 nm (187.54 THz) with band widths of 45.87 nm and 108.24 nm respectively. The field distributions of the proposed CRR with single slit is represented in figure 6 at two operating wavelengths of 1273.6 (235.74 THz) and 1598.3 nm (187.54 THz) respectively. The energy is more confinement on the metal insulator regions of the hybrid waveguide.

Figure 5. Simulation results of CRR using single slit varying parameters of (a) radius (R) (g1) varying parameters of (b) slit gap (g1)

Figure 6. 3D field distribution of the proposed CRR with single slit at two operating wavelengths (a) 1273.6 nm (235.74 THz) (b) 1598.3 nm (187.54 THz)
Figure 6. Field distributions of CRR using single slit at (a) 1273.6 nm (235.74 THz) and (b) 1598.3 nm (187.54 THz)

4. Design of CRR using Dual slit

A dual slit with a gaps g1 and g2 are included in the CRR and produces the proposed dual slit CRR represented in figure 7(a). The figure 7(b) shows the equivalent lumped model for figure 7(a). The capacitance effect is inserted in the CRR at top and bottom of the circular ring for enhancing the bandwidth. The design parameters are used for CRR with single slit is L1=200 nm, W1 =55 nm, g = 2 nm, g1 = 2 nm, g2 = 2 nm, r = 600 nm and d = 50 nm.

![Diagram of CRR design with dual slits]

Figure 7. (a) CRR structure using dual slit (b) Equivalent lumped model of CRR using dual slit

The simulated results of reflection coefficient and transmission coefficient of the CRR with dual slits by varying the radius (R) and gap of the slits g1 and g2 is represented in figure 8 (a) and (b). The optimized value of R is 600 nm, g1 and g2 are 2 nm. The simulated results of the CRR using dual slit operated in two wavelengths of 1245.1 nm (274.16 THz) and 1620.9 nm (185.17 THz) with band widths of 43.85 nm and 184.6 nm respectively.

![Simulation results of CRR using Dual slit varying parameters of (a) radius (R) (b) slit gaps (g1 and g2)]

Figure 8. Simulation results of CRR using Dual slit varying parameters of (a) radius (R) (b) slit gaps (g1 and g2)

The field distributions of the proposed CRR with single slit is represented in figure 9 at two operating wavelengths of 1245.1 (274.16 THz) and 1620.9 nm (185.17 THz) respectively. The energy is more confinement on the metal insulator regions of the hybrid waveguide. All the proposed filters are
best suitable for photonic integrated circuit applications and these are fabricated using e-beam lithography techniques.

![Figure 9](image)

**Figure 9.** Field distributions of CRR using single slit at (a) 1300 nm (186.95 THz) and (b) 1600 nm (230.79 THz)

5. Conclusion

Dual-band BPF are simulated and numerically analyzed using CRR and CRR with single and dual slits. The proposed devices are designed using standard ring resonator. The reflection and transmission characteristics of HMIM waveguide based CRR and CRR with single and dual slits observed the dual band BPF operation. The transmission performance is explained by the resonance conditions, which agrees with the numerical calculation. The paper provides a promising application for Photonic integrated optical circuits.

References

[1] M. Sumetsky, "Optimization of optical ring resonator devices for sensing applications," Opt. Lett, vol. 32, no. 17, pp. 2577-2579, 2007.
[2] Qianfan Xu, David Fattal, and Raymond G. Beausoleil, "Silicon microring resonators with 1.5-μm radius," Opt. Express, vol.16, no. 6, pp. 4309-4315, 2008.
[3] Y. S. Yi, D. C. Wu, P. Birar and Z. Yang, "Ring resonator-based optical hydrogen sensor", IEEE Sensors J., vol. 17, no. 7, pp. 2042-2047, Apr. 2017
[4] S. Zou, F. Wang, R. Liang, L. Xiao, and M. Hu, “A nanoscale refractive index sensor based on asymmetric plasmonic waveguide with a ring resonator,” IEEE Sensors J., vol.15, no. 2, pp. 646–650, 2013.
[5] Hong-Son Chu, Yuriy A. Akimov, Ping Bai, and Er-Ping Li, "Hybrid dielectric-loaded plasmonic waveguide and wavelength selective components for efficiently controlling light at subwavelength scale," J. Opt. Soc. Am. B, vol. 28, no. 12, pp. 2895-2901, 2011.
[6] Hong-Son Chu, Yuriy Akimov, Ping Bai, and Er-Ping Li, "Submicrometer radius and highly confined plasmonic ring resonator filters based on hybrid metal-oxide-semiconductor waveguide," Opt. Lett. Vol. 37, no. 21, pp. 4564-4566, 2012.
[7] Zhu S, Lo GQ, Kwong DL, "Submicron-radius plasmonic racetrack resonators in metal-dielectric-Si hybrid plasmonic waveguides," IEEE Photon Technol Lett, vol. 26, no. 8, pp. 833–836, 2014.
[8] S. Zhu, B. Lin, G. Lo and D. Kwong, "High-Performance TO Switches on Compact Cu-Dielectric-Si Hybrid Plasmonic WRRs," IEEE Photonics Technology Letters, vol. 26, no. 24, pp. 2495-2498, 2014.
[9] M. Weidenbach, D. Jahn, A. Rehn, S. F. Busch, F. Beltrán-Mejía, J. C. Balzer, and M. Koch, "3D printed dielectric rectangular waveguides, splitters and couplers for 120 GHz," Opt. Express, vol. 24, no. 25, pp. 28968-28976, 2016.
[10] Hong-Son Chu, Wei-Bin Ewe, and Er-Ping Li, “Tunable propagation of light through a coupled-
bent dielectric-loaded plasmonic waveguides,” J Appl Physics, Vol 106, no.10, pp.106101, 2009.
[11] Long Chen, Jagat Shakya, and Michal Lipson, "Subwavelength confinement in an integrated metal slot waveguide on silicon," Opt. Lett., vol. 31, no. 14, pp. 2133-2135, 2006.
[12] Pierre Berini, "Long-range surface plasmon polaritons," Adv. Opt. Photon., vol. 1, no. 3, pp. 484-588, 2009.
[13] K. Wen et al., "Spectral Characteristics of Plasmonic Metal–Insulator–Metal Waveguides With a Tilted Groove," IEEE Photonics Journal, vol. 4, no. 5, pp. 1794-1800, 2012.
[14] A. Boltasseva and S. I. Bozhevolnyi, "Directional Couplers Using Long-Range Surface Plasmon Polariton Waveguides," IEEE Journal of Selected Topics in Quantum Electronics, vol. 12, no. 6, pp. 1233-1241, 2006.
[15] Ozbay E, “Plasmonics: Merging Photonics and Electronics at Nanoscale Dimensions,” Science vol. 311, no.5758, pp.189-193, 2006.
[16] Alam M Z, Aitchison J S and Mojahedi M, “A marriage of convenience: Hybridization of surface plasmon and dielectric waveguide modes,” Laser Photon Rev., vol. 8, no. 3, pp. 394-408, 2014.
[17] M. Z. Alam, J. S. Aitchison and M. Mojahedi, "Theoretical Analysis of Hybrid Plasmonic Waveguide," IEEE Journal of Selected Topics in Quantum Electronics, vol. 19, no. 3, pp. 4602008-4602008, 2013.
[18] Li Wei, Sarah Aldawsari, Wing-Ki Liu, Brian R West, “Theoretical analysis of plasmonic modes in a symmetric conductor–gap–dielectric structure for nanoscale confinement” IEEE Photonics Journal, vol. 6, no. 3, pp. 1-10, 2014.
[19] M Nikoufard, N Heydari, S Pourgholi, A Rostami Khomami, “Novel hybrid plasmonic-based directional coupler on InP substrate”, photonics and Nanosturcttues, vol. 22, pp. 9-17, 2016.
[20] P. Sharma and V. D. Kumar, "Hybrid Plasmonic Waveguides and Bends," in 13th International Conference on Fiber Optics and Photonics, OSA Technical Digest (online) (Optical Society of America, 2016), paper W3A.65.
[21] P. Sharma and Dinesh Kumar V, “Hybrid metal insulator metal plasmonic waveguide and ring resonator,” 2016 21st optoelectronics and communications conference (OECC) held jointly with 2016 international conference on Photonics in Switching (PS), Niigata, Japan, 2016, pp.1-3.
[22] P. Sharma and V.D. Kumar, "Hybrid insulator metal insulator planar plasmonic waveguide-based components", IEEE Photonics Technol. Lett., vol. 29, no. 16, pp. 1360-1363, 2017.
[23] P. Sharma and Dinesh Kumar V., “Surface plasmon Bragg grating using Hybrid Metal insulator metal plasmonic waveguide”, in 39th PIERS in Singapore, pp.2747-2751, 2017.
[24] P. Sharma and V.D. Kumar, "All optical logic gates using hybrid metal insulator metal plasmonic waveguide", IEEE Photonics Technol. Lett., vol. 30, no. 10, pp. 959-962, 2018.
[25] Sharma P, Dinesh Kumar V, “Multilayer Hybrid Plasmonic Nano Patch Antenna” Plasmonics, vol.14, pp. 435–440, 2019.