سوئیچ پلاسمونیک مبتنی بر تشدیدگر حلقوی مربعی با خم‌های هموار

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چکیده – دراین مقاله سوئیچ‌های تمام نوری مبتنی بر تشدیدگرهای مربعی شکل با خم‌های هموار بررسی شده است. سوئیچ‌های سه و چهار پورتی به روش عددی تفاضل محدود در حوزه زمان شبیه‌سازی و بررسی شده‌اند. نشان داده شده است که با اعمال اثر غیرخطی مدولاسیون خودفازی، توان سوئیچینگ در سوئیچ‌های پلاسمونیک چهار پورتی برای رسیدن به نسبت توان خروجی 12.77dB **برابر** *(kW/m)* 11.84 **است. درحالی‌که در سوئیچ‌های سه‌پورتی با توان سوئیچینگ** *(kW/m)* 12 **می‌توان به نسبت توان خروجی** 16.8dB **دست یافت. سوئیچ‌های تمام نوری مبتنی بر تشدیدگرهای مربعی به‌دلیل ابعاد در مقیاس نانو و توان سوئیچینگ پایین، برای استفاده در مدارهای مجتمع نوری بسیار مناسب هستند.**

کلید واژه- پلاسمون‌های سطحی، تشدیدگرهای حلقوی، سوئیچ غیرخطی، مدولاسیون خودفازی.

Plasmonic Square Ring Resonator Switch with Smooth Corner Bends

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Abstract- In this paper, all-optical switches based on plasmonic square ring resonator (PSRR) with smooth corner bends have been proposed. Both three and four ports nonlinear switches have been numerically analyzed and simulated by the finite-difference time-domain (FDTD) method. By applying Kerr nonlinear self-phase modulation (SPM) effect, it has been shown that in four port switches the output power ratio of 12.77dB can be achieved by the switching power of 11.84 (*kW/m*), whereas the switching power of 12 (*kW/m*) is needed for attaining the power ratio of 16.8dB in three port switches. PSRRs are suitable for using in photonic integrated circuits as all-optical switches because of their nanoscale size and low required switching power.

Keywords: Nonlinear plasmonic switch, Plasmonic ring resonators, Self-phase modulation (SPM), Surface plasmon.

1 Introduction

Design and fabrication of optical devices based on surface plasmon polaritons (SPPs) have been attracted many research attentions because of their subwavelength scales and high confinement of lightwave. SPPs are the interaction of electromagnetic waves and the oscillations of electrons in metal, propagating on the metal-dielectric interfaces [1, 2]. Between various structures of plasmonic waveguides metal-dielectric-metal (MDM) structure is one of the best candidates for utilizing in optical devices because of its high confinement of the lightwave, low bending loss and acceptable propagation length [3]. Different passive and active MDM-based optical structures such as Bragg reflectors [4], wavelength sorters, couplers [5], stub waveguides, Y-splitters [6], Mach-Zehnder interferometers [7], and optical switches have been studied so far [8-10].
Ring resonators have been used for many applications, such as mode-selection, filtering and wavelength multi-demultiplexing [1, 11]. One of the considerable applications of ring resonators in the optical communication networks is switching which can be achieved by nonlinear effects, such as Kerr effects or other tunable procedures [8, 12]. Both circular and rectangular plasmonic ring resonators have been numerically and experimentally investigated [13-17].
Plasmonic waveguides with sharp bends have high transmission with low bending loss compared to the dielectric ones [11]. Rectangular ring resonators have high coupling efficiency compared to the circular ones due to the long coupling section between the bus waveguide and the resonator [15].
In this paper, we propose three and four ports all-optical switches based on PSRR with smooth corner bends. Kerr nonlinear self-phase modulation (SPM) effect is utilized to control the lightwave in our nanoscale plasmonic switch. The subwavelength size and the low required switching power of the PSRR switch makes it suitable for using in photonic integrated circuits (PICs).
The paper is organized as follows. In Section 2, the modeling and simulation method and in Section 3, the simulation results of the nonlinear PSRR switch containing smooth corner bends are described and discussed. The paper is concluded is Section 4.

2 Modeling and Simulation Method

The schematic view of the PSRR containing smooth corner bends between two parallel straight waveguides is shown in Figure 1. The parameters of the structure are the width of the waveguides and resonator (d), the gap between the waveguides and resonator (g), the effective radius (r) and the side length of the ring resonator in the x (L_x) and z (L_z) directions, the values of which are given in Table 1. These parameters are chosen such that the ring resonates at the wavelength of 1535nm in the third telecommunication window. The incident wave is launched from the port 1. The ON/OFF resonant conditions depend on the incident optical wavelengths, which would affect the interferences inside the ring and waveguides.

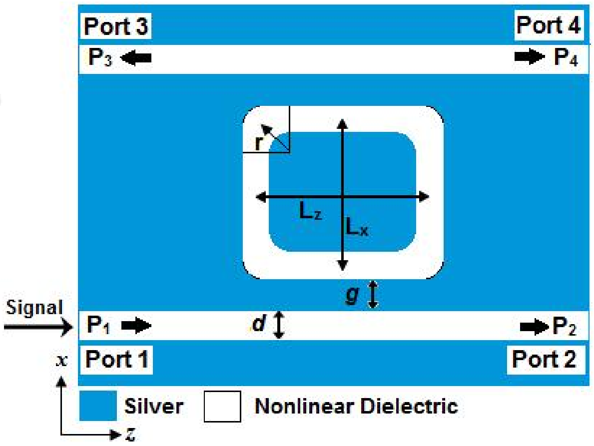


Figure 1: Schematic view of the plasmonic PSRR switch with smooth corner bends.

Table 1: Appropriate dimensions of the PSRR switch to resonate in the third telecommunication window. All values are in nanometer scale.

L_x	L_z	*d*	*g*	r
590	590	50	20	75

The metal and the dielectric are chosen to be silver and Au:SiO_2 composite, respectively. The metal-dielectric composite materials are used in the structure, because they have a large third-order nonlinear susceptibility, $\chi^{(3)}$, which is important for switching function [12]. The dispersive dielectric function of the silver is described by the Drude model, $\varepsilon(\omega)=\varepsilon_\infty-\omega_P^2/\left(\omega^2-j\gamma_P\omega\right)$, where $\varepsilon_\infty=1.95$ is the relative permittivity at infinite frequency, $\omega_P=1.37\times10^{16}\ (\text{rad/s})$ and $\gamma_p=20\times10^{12}\ (\text{rad/s})$ are the plasma and collision frequencies, respectively [9]. The refractive index of the nonlinear dielectric is $n=n_0+n_2I$, where $n_0=1.47$ and $n_2=2.07\times10^{-9}\ \left(cm^2/W\right)$ are the linear and nonlinear refractive indices, respectively, and I is the optical intensity [10]. The resonant wavelength of the rectangular ring resonator is determined by the equation [1]:

$$Ln_{eff}=m\lambda,\quad m=1,2,\ldots \tag{1}$$

where $L=2(L_x+L_z)$ is the effective length of the ring, n_{eff} and λ are the effective refractive index of the ring and the free space wavelength, respectively.
We have used the two-dimensional finite-difference time-domain (2D-FDTD) numerical method with a convolutional perfectly matched layer (CPML) as the absorbing boundary condition, to study the performance of our proposed nonlinear switch. The

grid size of the FDTD cell in x and z directions are $\Delta x = \Delta z = 1\text{nm}$ and the time step for numerical convergence due to Courant condition is $\Delta t = 0.95/\left(c\sqrt{(\Delta x)^{-2} + (\Delta z)^{-2}}\right)$, where c is the free space speed of light. Since the width of the waveguide is much smaller than the operating wavelength, only the fundamental TM mode is supported

3 Results and Discussion

By launching a Gaussian pulse to the port 1, the transmittance spectra at the output ports, defined as the ratio of the power at each port to the input power are depicted in Figure 2.

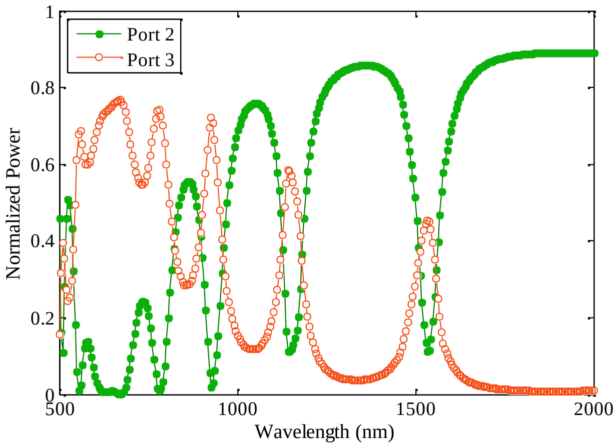


Figure 2: Transmittance spectra of the PSRR switch of Fig. 1 with smooth corner bends.

Since the plasmonic structures have much higher loss compared to the dielectric ones, the transmission is not 100%. As shown, one of the resonant wavelengths of the ring is 1535nm in the third telecommunication window. By using Equation (1) and choosing appropriate parameters for the PSRR switch of Figure 1, the ring resonates at 1535nm. We consider this wavelength for studying the switching performance of the filter.

To show the switching performance of the nonlinear PSRR switch, a high power CW signal at the wavelength of 1535nm is launched to the port 1. By increasing the input power, the refractive index of the dielectric ring resonator and so the resonant wavelength increase. Therefore, the output power at port 3 decreases and the power exits from port 2.

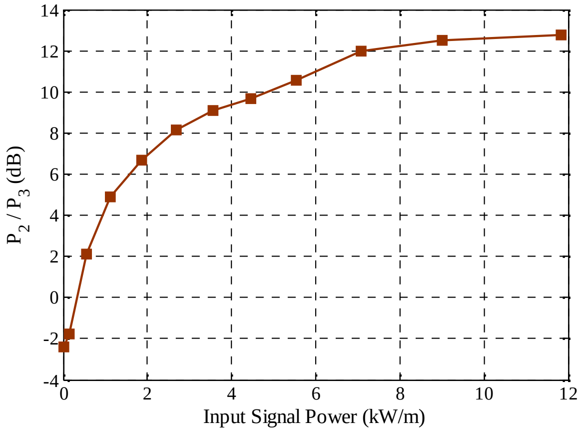
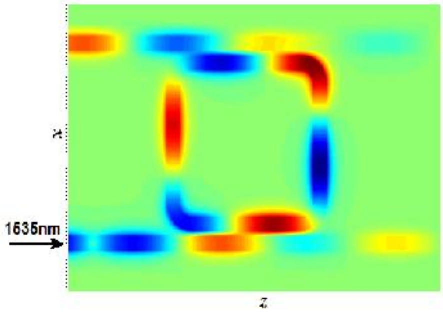
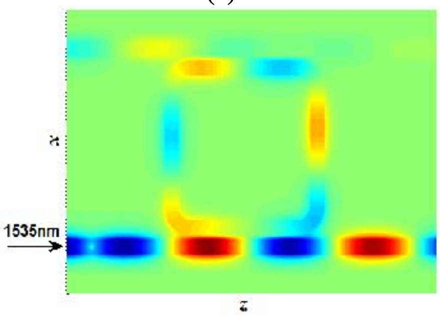


Figure 3: Output power ratio versus input power for the four port nonlinear switch of Fig. 1.



(a)



(b)

Figure 4: Magnetic filed distributions of the nonlinear PSRR switch of Fig. 1 at (a) low input power of $2.12\times10^{-5}\,(kW\ /m)$ and (b) high input power of 11.84 (*kW/m*) at 1535nm.

The output power ratio, defined as the ratio of the power at port 2 to the power at port 3 (P_2/P_3), increases from -2.4dB to 12.77dB, when the input light power increases from $2.12\times10^{-5}\,(kW\ /m)$ to 11.84 (*kW/m*), as depicted in Figure 3. In the high input power of 11.84 (*kW/m*), the ring is at OFF resonant condition and the wave exits from port 2.

The magnetic field distributions at low and high input powers that the ring is respectively at ON and OFF resonances are demonstrated in Figure 4. At ON resonance, the incident wave couples to the ring and decouples to port 3, so there is no wave at port 1. When the wave propagates in the ring, couples to the left and right of the lower waveguide. The lightwaves transmit in the right waveguide would diminish each other due to the destructive interference.

Next, we consider a three port nonlinear plasmonic switch illustrated in Figure 5. The parameters values of this switch are similar to the nonlinear switch of

Figure 1, so the wavelength of 1535nm is one of the resonant wavelengths of the structure.

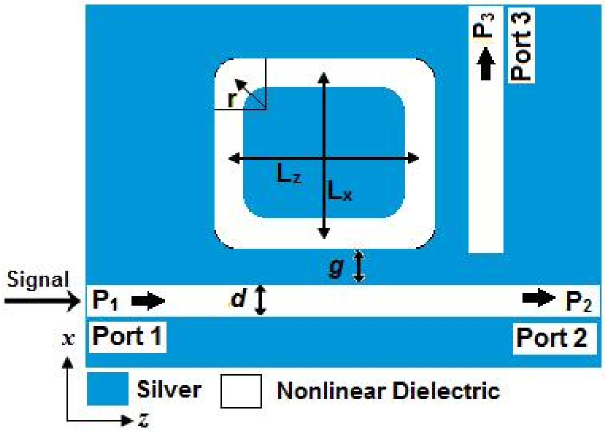


Figure 5: Schematic view of the three port PSRR switch with smooth corner bends.

To compare the required switching powers of the nonlinear switches of Figures 1 and 5, the output power ratio versus the input power at the resonant wavelength of 1535nm is depicted in Figure 6.

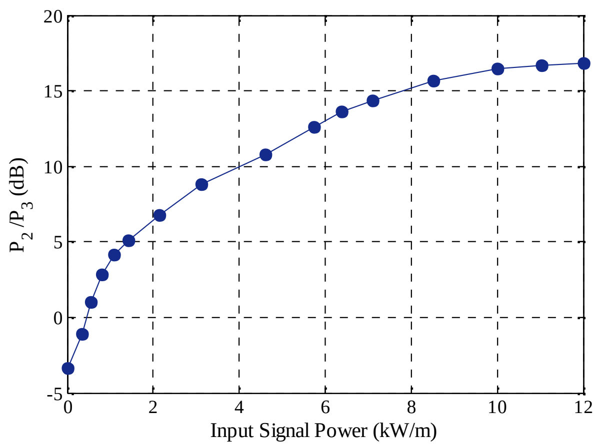


Figure 6: Output power ratio versus input power for the three port nonlinear switch of Fig. 5.

As shown in three port switch the output power ratio of 16.8dB can be achieved by the input signal power of 12(*kW/m*). Therefore, in three port switch we need lower switching power to attain the same output power ratio, compared to the four port one.

4 Conclusion

In this paper, the switching performance of a nonlinear PSRR switch with smooth corner bends between two parallel straight waveguides has been studied. By applying the input lightwave in the low and high intensities, the ring resonator, filled with a Kerr nonlinear material, can be in the ON/OFF resonant conditions, respectively. Therefore, the nonlinear PSRR switch can operate as an all-optical switch with subwavelength dimensions. By applying the Kerr nonlinear self-phase modulation (SMP) effect, it has been shown that in four port switch the switching power of 11.84 (*kW/m*) is required to attain the output power ratio of 12.77dB, whereas in three port switch, the power ratio of 16.8dB is obtained by applying the switching power of 12 (*kW/m*). PSRR switches are suitable for using in photonic integrated circuits (PICs) as all-optical switches because of their nanoscale size and low switching power.

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