Nanoscale plasmonic circulator

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Abstract. Breaking time reversal symmetry of the light flow, implying optical wave isolation and directional light guiding, is crucial for signal handling and integrated optics. Such signal isolation is possible with an optical circulator—a three-port magneto-active nonreciprocal device, which transmits light from any of its input ports into the next port in a circular order, isolating the remaining port. Small magneto-optical activity at optical frequencies challenges the miniaturization and further on-chip integration of this key fundamental component. Here we demonstrate theoretically that by employing principles of plasmonic mode engineering it is possible to enhance significantly magneto-optical response in a deep subwavelength regime and suggest a conceptual approach for a design of an ultracompact nanoscale passive optical circulator. This work paves the way for future generation of nonreciprocal integrated optics with a nanoscale on-chip compatibility.

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1. Introduction

Advances in nanophotonics and plasmonic optics in recent years have provided miniaturization of optical devices and components suitable for on-chip integration \[1–3\]. In particular, some of the basic passive and active nanoscale optical integrated circuit elements including interconnects, beam splitters, switches and other components have been demonstrated recently \[4\]. At the same time, fully functional signal processing in nanophotonics requires design of nonreciprocal elements, such as isolators or circulators (analogous, e.g., with advances in microwave technology \[5, 6\]).

Such nonreciprocal characteristics are achieved with materials exhibiting time-reversal symmetry breaking, such as magneto-optic (MO) materials. (Other possibilities include utilizing nonlinearities \[7–9\] or materials having time dependent properties \[10, 11\].) However, at optical frequencies the magneto-optical response is usually weak, which results in a bulky and inefficient design of basic nonreciprocal optical components, not usually compatible with on-chip integration. For example, ‘conventional’ three port optical circulators are typically more than several hundred microns large (i.e. \(\gg \lambda \simeq 1 \mu m\)) \[12, 13\].

Progress in silicon photonics and magneto-photonic crystals promises a substantial miniaturization of key nonreciprocal optical devices. For instance, an on-chip silicon-based optical isolation \[14\], one-way edge state propagation \[15, 16\] and compact photonic crystal circulators comparable with the operating wavelength (i.e. \(\gg \lambda\)) \[17–20\] have been suggested and demonstrated recently. However, further size reduction of conventional dielectric devices down to the subwavelength scale \((\leq \lambda)\) encounters fundamental challenges due to the light diffraction limit.

This is where highly confined surface plasmons—electromagnetic fields at metal surfaces—can be exploited in order to extend the technology beyond the diffraction limit \[3, 21\]. Furthermore, strong light localization in plasmonic structures can lead to a considerable increase of the nonreciprocal response. The latter was successfully implemented resulting in a significant enhancement of Kerr and Faraday effects \[22–27\].

In our other work \[28\] we have shown that plasmonic nanorod structures possessing a rotational symmetry, when immersed in magneto-optical media, exhibit a strong azimuthal symmetry breaking. In particular, it has been suggested that rotational symmetry of the structure gives rise to an eigenmode degeneracy at some of the plasmonic resonances. (It is worth mentioning here that the study of axially symmetric plasmonic nanoclusters \[29, 30\] and oligomers \[31\] with high quality resonances has emerged recently as a rapidly developing and exciting field.) In presence of magneto-optical activity a strong mode interaction occurs yielding a frequency splitting of these degenerate states which can be described by a simple empirical formula: \(\omega_{\pm} = \omega_0(1 \pm C\alpha)\), where \(\pm\) correspond to two counter-rotating states formed in the process of interaction, \(\omega_0\) is the resonant frequency at which the mode degeneracy is observed, \(\alpha\) is the strength of magneto-optical activity and \(C\) is the intermodal coupling constant depending on the eigen-mode configuration. Note that an analogous symmetry breaking mechanism between the counter-rotating states was employed to design a compact photonic crystal circulator in \[17, 18\]. Our recent study of the light scattering from such nonreciprocal nanostructures revealed that the symmetry breaking between the counter rotating states leads to a strong near-field power flow circulation resulting in the tilt and rotation of the scattered radiation pattern \[28\].
Here, based on our results from [28] we propose a design for an ultracompact nanoscale plasmonic circulator, exploiting the above-mentioned mechanism of rotation of scattering from subwavelength plasmonic nanorod structure in the presence of MO materials. Such a nanoscale circulator with an on-chip comparability can serve as a platform for fully functional future generation optical networks and integrated circuits.

2. Results

Figure 1 shows the geometry of the proposed three-port junction circulator. For the sake of simplicity in the analysis and numerical simulations, and without loss of generality, we assume our system to be a two-dimensional structure, i.e. without field variations in the $z$-direction. The circulator consists of three single-mode dielectric waveguides of width $a$ coupled with a plasmonic structure consisting of metallic nanorods with deeply subwavelength diameters immersed in MO medium as shown in figure 1. It is assumed that the MO medium is magnetized along the $z$-direction, and therefore, its relative permittivity function is described by an antisymmetric tensor

$$\tilde{\varepsilon} = \begin{pmatrix} \varepsilon_{\text{mo}} & i\alpha & 0 \\ -i\alpha & \varepsilon_{\text{mo}} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{pmatrix},$$

where $\varepsilon_{\text{mo}}$ and $\varepsilon_{\perp}$ are diagonal components, $\alpha$ is the off-diagonal component responsible for the ‘strength’ of MO (nonreciprocal) activity of the medium. The parameter $\alpha$ is usually very small at optical frequencies (of the order of $10^{-2}$ or less). For example, bismuth iron garnet (BIG) exhibits $\varepsilon_{\text{mo}} = 6.25$, $\alpha = 0.06$ and small optical losses [32]. In order to better understand the system dynamics of our proposed structure, in our theoretical studies we assume $\alpha$ ranging from zero to 0.15.
The plasmonic structure consists of a metallic nanorod with radius $R = 50$ nm surrounded by three other metallic nanorods with radii $R_s = 10$ nm as shown schematically in figure 1. The distance between the centers of thinner and thicker nanorods is 80 nm. It is assumed here that the metal relative permittivity to be fixed at $\varepsilon_m = -10$, and, if not stated otherwise, the system is assumed to be lossless. Note that, for the sake of simplicity in our analysis and optimization we keep the material permittivities independent of frequency. This does not introduce any limitation in our concept, since the dispersion of the material parameters can be easily included in the original design of the system.

This four-nanorod structure is placed in a uniform magnetized BIG host. At $\lambda \simeq 1.4 \mu m$ and the parameters chosen above, this system exhibits a sharp plasmonic resonance, a strong near-field power flow circulation and rotation of the near-field scattering at this resonance (not shown here, but in full accordance with our results shown in [28]). Integrating this structure into the core of the three-port junction, as shown in figure 1, we expect that the near-field circulation cause the asymmetric and nonreciprocal power redistribution into the output arms of the junction. In order to demonstrate our predictions we numerically study the circulator operation with a finite-element-based method in the COMSOL Multiphysics™.

Consider first a magnetically inactive system, i.e. unmagnetized case when $\alpha = 0$. In this case no asymmetry or nonreciprocity is present and the system behaves as a symmetrical beam splitter, i.e. signal launched into one of the ports is distributed symmetrically and equally between the two output ports of the junction. We search for the optimum regime of beam splitter operation in order to maximize the output power and reduce the radiation losses. For this reason we scan over the wavelength range near the structure resonance, and by varying the junction parameters we trace for the maximum power transmission. Following this procedure and for the given parameters here we find that the optimum width of waveguides is $a = 350$ nm and their permittivity is $\varepsilon = 3$. For matching purposes, transition waveguides of length $L = 0.9 \mu m$-long with permittivity 3.5 are introduced (see figure 1) in order to reduce backscattering and increase the transmission. Note that by placing the structure into the core of the junction its resonance is shifted to 1.43 $\mu m$ due to a change in boundary conditions.

In figure 2(a) we plot the simulation results, performed by the Software package COMSOL Multiphysics™, for the $z$-oriented magnetic field distribution at the resonance for a signal launched into port 1. Clearly a symmetric beam splitting into the other two output arms is observed. In order to trace the operation efficiency we study the normalized power transmission $S_{21(31)} = P_{\text{out}}^{2(3)} / P_{\text{in}}$ with frequency variation, see figure 4(a). A strong transmission resonance at free-space wavelength $\lambda \simeq 1.43 \mu m$, which corresponds to the plasmonic resonance of the entire structure, is observed. At the resonance, the power output at each of the ports 2 and 3 ($S_{21} = S_{31}$) reaches up-to 33% and then steeply decreases with frequency detuning. The strong dependence and correlation between the power output and the structure excitation reveals a crucial role of structure resonance in the junction operation. The structure being an efficient plasmonic scatterer when excited redistributes the input power between the junction arms, i.e. ‘directionally’ scatters the input signal and thus increasing the out-coupling efficiency. Off resonance the scatterer is not excited as much, and therefore the system behaves as a conventional photonic Y-junction splitter, which is rather inefficient due to a large angle between the junction arms so that most of the input power is radiated away. Note that, despite of significant increase in transmission with the use of the nanostructure at its resonance, the radiation losses remain quite high; however we believe that further geometry optimization, including the redesign of the plasmonic structure itself, will increase the performance.
Figure 2. Simulation results for the distribution of the $z$-oriented magnetic field ($H_z$) in the circulator: (a) nonmagnetized ($\alpha = 0$), and (b), (c) magnetized ($\alpha = 0.1$) systems, respectively. Arrows show the direction of the power flow. Numbers 1–3 label the ports of the circulator. Free-space wavelength is $\lambda = 1.43 \mu m$.

As the next step, we introduce the MO activity ($\alpha \neq 0$) and study its influence on the circulator operation. Figure 2(b) shows the numerical results for the $z$-oriented magnetic field distribution for the input signal launched into the port 1 at the resonance frequency ($\lambda = 1.43 \mu m$) when $\alpha = 0.1$. In this case a substantial breaking of the symmetry between the output at ports 2 and 3 is observed. The power is predominantly guided into the arm 2, while the other arm carries much less power. To reveal the mechanism of such strong symmetry breaking we study the near-field distributions for biased and unbiased systems (see figures 3(a) and (b)). The near-field pattern in the unbiased case (figure 3(a)) is symmetric and resembles that of a ‘point’ magnetic quadrupole. Such near-field distribution ensures a strong and symmetric coupling between the junction arms and the structure. When MO activity is introduced the nearfield radiation is tilted and rotated [28]. This rotation of the scattering pattern leads to the change of coupling between the structure and the junction arms, so that input (port 1) and only
Figure 3. Snapshot in time of the near-field distribution of the magnetic field ($H_z$) excited at the resonance of the plasmonic structure ($\lambda = 1.43 \, \mu m$): (a) nonmagnetized ($\alpha = 0$) and (b) magnetized ($\alpha = 0.1$) systems, respectively. The arrows show schematically the coupling between input port and the two output ports.

one of the output (port 2) waveguides are coupled efficiently with the structure. Furthermore, we notice from figure 3(b) that a predominantly antisymmetric field profile is induced at the entrance of one of the output arms (port 3 in this case), which is why the single-mode waveguide is not excited, causing strong isolation of the corresponding port, as shown in figure 2(b). We note that the suggested mechanism of circulator operation based on the scattering and the rotation of the scattering differs conceptually from the well established interference principle employed in the conventional circulator designs [5].

Next we trace the circulator performance as a function of wavelength when $\alpha = 0.1$ and the permittivity of the metallic nanorods is kept fixed at $-10$ (see figure 4(a)). A resonant behavior is clearly observed, which manifests the role of the structure in the circulator operation. At resonance the power transmitted to port 2 comprises up-to 63% of the input power, whereas less than 3% is transmitted from port 1 to port 3, demonstrating a good isolation of the corresponding port. We note that 63% of power output observed in the biased case is in fact about 96% of total power output in the unbiased case (33 + 33%), meaning that the radiation losses in the biased regime stay almost the same as in the unbiased one.

In figure 4(b) the transmission at ports 2 and 3 as a function of MO activity parameter $\alpha$ at $\lambda = 1.43 \, \mu m$ is plotted. We observe a growth of power output for the port 2 with a corresponding increase of isolation for the port 3. The transmission through port 2 peaks with maximum of 64% when $\alpha = 0.11$ and begins to decline with a subsequent increase of $\alpha$. For small values of $\alpha$ we observe linear dependence of transmission and isolation on $\alpha$ which correlates well with the empirical formula describing the frequency splitting between the counter rotating states [28]. The deviation from the linear dependence with growth of $\alpha$ can be explained by slight shift of resonance frequency and the change of coupling efficiency between the output waveguides and the structure due an ‘over rotation’ of the near-field pattern. We note that at $\alpha = 0.06$ corresponding to the realistic levels achieved in BIG we observe about 54% of transmission from port 1 to port 2 and less than 10% from port 1 to port 3.
In order to underline the nonreciprocal nature of the proposed plasmonic circulator we launch an input signal from port 2. In this case we clearly see that light is mainly guided into port 3, whereas port 1 is isolated, as expected. Hence, the device when biased transmits the signal from any port to the next port (in circular order). Changing the direction of magnetization will swap the output and isolated ports, as also expected. Note also that the design principle we utilized based on the scattering from the structure provides the potential for the design of a circulator with higher number of ports.

Finally, we study the influence of losses on the performance of the proposed circulator. For this purpose we consider the metal to be lossy, described by a complex permittivity $\varepsilon_m = -10 - 0.01i$. Figure 5 shows the transmission as a function of wavelength for both output and isolated ports when $\alpha = 0.1$ and $\varepsilon_m = -10 - 0.01i$. Clearly the symmetry breaking in transmitted power between the output ports is still observed. Again a resonant transmission through one of the ports only is achieved, while the other output port is isolated. However, as expected the losses result in decrease in the total power transmission, and a decrease in the isolation ratio, i.e. the ratio of transmitted powers through both output ports. The ability to keep the circulator performance with losses may allow the possibility of implementing ferromagnetic metals possessing stronger MO activity (such as, e.g., Co, Ni, Fe). Although these materials exhibit quite high electromagnetic damping, their combination with plasmonic noble metals and proper structure engineering might give the possibility to control the effects of the losses and the MO activity [23, 24].

3. Conclusions

In summary, we have proposed a design for a subwavelength three-port junction circulator with an integrated plasmonic structure. We have demonstrated numerically that the plasmonic resonance and the rotation of corresponding near-field scattering in presence of MO activity

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**Figure 4.** Transmission properties of the circulator. (a) Variation of the circulator power transmission into the port 2 and isolation of the port 3, as a function of wavelength for biased ($\alpha = 0.1$) and unbiased ($\alpha = 0$) cases. (b) Variation of the circulator power transmission as a function of MO activity parameter at the free space wavelength ($\lambda = 1.43 \, \mu\text{m}$). To explore the performance of this circulator based on its spatial dispersion, here and in figure 5 we assume that the metal permittivity is frequency independent and fixed at $\varepsilon_m = -10$. 
lead to the breaking of symmetry in the power output between the circulator arms. Our analysis reveals up-to 63% of power transmitted through one of the output ports, with almost complete isolation for the other output port of the circulator. Finally, we study the influence of losses and find that despite the decrease of net output in lossy systems, the symmetry breaking between the output ports remains relatively high. This concept may find useful application in integrated nanophotonics, optical metatronics and signal handling in on-chip integrated circuits.

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Figure 5. The effect of metal losses on the circulator performance. Power transmission as a function of wavelength for $\alpha = 0.1$ is plotted for the output and isolated ports. As in figure 4, here metal permittivity is assumed to be frequency independent and fixed at $\varepsilon_m = -10 - 0.01i$. 

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