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Coin paradox spin-orbit interaction enhances magneto-optical effect and its application in on- chip integrated optical isolator

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Abstract: We designed a simple on-chip integrated optical isolator made up of a MIM waveguide and a disc cavity filled with magneto-optical material to enhance the transverse magneto-optical effect through the coin paradox spin-orbit interaction (SOI). The simulation results of the non-reciprocal transmission properties of this optical structure show that a high-performance on-chip integrated optical isolator is obtained. The maximum isolation ratio (IR) is greater than 40 dB with a corresponding insertion loss (IL) of about 2 dB. The great performance of the optical isolator is attributed to the strong transverse magneto-optical effect, which is enhanced by the coin paradox SOI. Moreover, the enhancement of the transverse magneto-optical effect through the coin paradox SOI is more substantial for smaller azimuthal mode number n . Benefitting from this, the transverse magneto-optical effect remains strong in a wide wavelength range. Additionally, a smaller cavity has a stronger transverse magneto-optical effect in the same wavelength range. Our research provides a new perspective for creating highly integrated magneto-optical devices.

Keywords: coin paradox, Spin-orbit interactions, Magneto-optic effect, isolator

Introduction

Optical isolators based on non-reciprocal transmission, are the key photonic elements in optical telecommunications and optical information. To achieve a more integrated optical isolator,

25 many methods, such as the use of magneto-optical effects [1-5], topology [6], nonlinear effects
26 [7-12], parity-time symmetry breaking [13-15], have been developed. Among these, the
27 magneto-optical effect is still a hotspot. So far, however, the devices created, have typically
28 been in large scales [2,16] because the magneto-optical effect is mostly weak in these cases.

29 SPP can break the diffraction limit [17,18] and has excellent potential in integrated optics
30 [19–21], especially after the improvement in the problem regarding high loss of SPP [22]. SPP
31 has transverse spin angular momentum (TSAM) [23-25], which can induce a magneto-optical
32 effect to realize a non-reciprocal transmission similar to the longitudinal spin angular
33 momentum (LSAM) of light [26-28]. However, it is difficult to miniaturize the isolator based
34 on the transverse magneto-optical effect of SPP due to the weak magneto-optical effect. There
35 are two key reasons resulted in the weak transverse magneto-optical effect of SPP; one is the
36 small magneto-optic coefficient of the magneto-optic materials, and the other is that the
37 transverse spin of SPP is not circular, but elliptical [26]. At present, a variety of magneto-optical
38 materials with large magneto-optic coefficients have been fabricated and applied to light
39 isolators [4,29-32]. This brings hope for creating miniaturized optical isolators with plasmonic
40 structures. But, on the other hand, the elliptical transverse spin of SPP is still the bottleneck for
41 the application of the transverse magneto-optical effect. The discovery of new methods to
42 enhance the transverse magneto-optical effect is still desired.

43 Spin and orbital angular momenta (SAM and OAM) are two distinct light components.
44 These can interact with each other effectively, that is, via spin-orbit interactions (SOI). Many
45 essential and valuable optical effects based on SOI of light have been discovered, including
46 spin Hall effect, quantum spin Hall effect, topology, etc. Coin paradox is a fascinating natural
47 phenomenon, which shows a distinctive SOI, that circumferential orbit causes the rotation of
48 the spin change. Thus, coin paradox SOI may be a new physical mechanism to regulate the
49 transverse magneto-optical effect of SPP.

50 This work reports the design of a simple on-chip integrated optical isolator composed of a
51 MIM waveguide and a disc cavity filled with a magneto-optical material. In this optical isolator
52 structure, the effective enhancement of the transverse magneto-optical effect was confirmed
53 through coin paradox SOI. Benefitting from the enhanced transverse magneto-optical effect in
54 the optical isolator structure, the forward and backward resonant valleys in the transmission
55 spectra were wholly separated from each other when $\varepsilon_{xy} \geq 0.04$. A high-performance on-chip
56 integrated optical isolator was obtained, for which the maximum isolation greater than 40 dB
57 was obtained, with a corresponding IL of about 2 dB. Due to the unique properties of coin
58 paradox SOI in the optical isolator structure, that the improvement of the transverse magneto-
59 optical effect is more substantial for smaller azimuthal mode number n . The transverse
60 magneto-optical effect remained strong in a wide wavelength range. Furthermore, a greater
61 transverse magneto-optical effect appeared in a smaller disc cavity, which could effectively
62 surmount the broadening of the resonance valleys induced by the smaller cavity. The strong
63 transverse magneto-optical effect structure developed herein, has huge application potential in
64 on-chip highly integrated magneto-optical devices, optical isolators, magneto-optical switches,
65 magnetic sensors, etc.

66 Methods

67

68 **Fig.1** Schematic illustration of the optical isolator structure composed of a MIM waveguide and a disc
 69 cavity. The MIM waveguide and the disc cavity are filled with magneto-optical material and remain
 70 under a static magnetic field.
 71 Fig. 1 shows the schematic illustration of the proposed optical isolator structure composed of
 72 a MIM waveguide and a disc cavity. The radius (R) of the disc cavity was set to 500 nm, the
 73 width of the MIM waveguide was set to $d=50$ nm and the gap between the disc cavity and the
 74 MIM waveguide was set to $g=20$ nm. The metal is silver, whose frequency-dependent
 75 complex relative permittivity is characterized by the Drude model:

$$76 \quad \varepsilon_m(\omega) = \varepsilon_\infty - \omega_p^2 / \omega(\omega + i\gamma) \quad (1)$$

77 Here, ε_∞ is the dielectric constant at an infinite frequency, γ is the electron collision frequency,
 78 ω_p is bulk plasma frequency, and ω is the angular frequency of the incident light. The
 79 parameters put into Eq. (1) were $\varepsilon_\infty=3.7$, $\omega_p=9.1$ eV, $\gamma=0.018$ eV [33]. In order to excite the
 80 SPPs, the input light was set to transverse magnetic (TM) plane wave.

81 The disc cavity and the MIM waveguide were filled with magneto-optical material, and a
 82 static magnetic field is applied. The effect of static magnetic field on magneto-optical
 83 materials was largely reflected in the dielectric tensor of materials. For anisotropic magneto-
 84 optical materials, a static magnetic field $\mathbf{B}$ can be applied along the z-direction, where the
 85 dielectric tensor can be expressed as:

$$86 \quad \boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & -i\varepsilon_{xy} & 0 \\ i\varepsilon_{xy} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix} \quad (2)$$

87 The magneto-optical material is set to be Bismuth-doped Yttrium Iron Garnet (Bi: YIG).
 88 Garnet belongs to the cubic crystal structure and is isotropic, so the diagonal elements of its
 89 dielectric tensor are identical, that is, $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = \varepsilon_0 = n^2$. The dielectric constant ε_0

of the diagonal element is set to 4.84, the typical refractive index of YIG near the wavelength of 1.5 μm [34]. If the material absorption is ignored, the dielectric tensor must be in the Hermitian matrix form $\varepsilon_{xy} = \varepsilon_{yx}^*$. This also means that ε_{xy} must be a real number. Recently, experiments have proved that the ε_{xy} can be greater than 0.3 [35] and the theoretically predicted ε_{xy} [36] is much greater than that obtained by experiment. In this work, the value of ε_{xy} was set from 0 to 0.3.

Commercial software COMSOL Multiphysics was employed for model building and simulation calculations based on the finite element method (FEM). For the convenience of research, the whole structure was two-dimensional. The passing Poynting vector $\mathbf{S}$ was integrated at the entrance and exit ends to obtain the entrance energy P_{in} and the exit energy P_{out} , $P_{in} = \int \mathbf{S}_1 ds_1$, $P_{out} = \int \mathbf{S}_2 ds_2$ and the transmittance $T = -10 \lg(P_{out} / P_{in})$ dB. Light input was given from the left of the MIM waveguide, and its output from the right is labeled as ‘forward’ in this paper. Contrarily, the light input from the right of the MIM waveguide resulted in the output from the left, and called ‘backward’.

Results and discussion

107 **Fig. 2** The total transmission spectra of the optical isolator structures for different ε_{xy} . The solid black
108 line shows the transmission spectrum for $\varepsilon_{xy} = 0$, solid red line for $\varepsilon_{xy} = 0.3$ forward and the dotted
109 red line for $\varepsilon_{xy} = 0.3$ backward. The insets below the transmission spectra are the intensity distributions
110 of the z component of the magnetic field, corresponding to the case of $\varepsilon_{xy} = 0$

111 As shown in Fig. 1, the disc cavity supports a fascinating coin paradox SOI. For example, for
112 the mode $TM_{(0,n)}$, the transverse spin and the orbit rotation of SPP lie in the same direction.
113 SPP travels around the disc cavity one turn, and the electric field vector rotates $n+1$ turns. The
114 circular orbit causes the extra turn. This effect is similar to the coin paradox and forms a
115 unique SOI. The coin paradox SOI is more significant for smaller n . The simulation results
116 confirm that the coin paradox SOI can enhance the transverse magneto-optical effect
117 effectively.

118 Fig. 2 shows the transmission spectra of the optical isolator structures for different ε_{xy} .
119 For the case of $\varepsilon_{xy} = 0$, forward and backward transmission spectra overlap, the transmission
120 spectrum is shown as solid black line. The solid red line shows the transmission spectrum for
121 the case of $\varepsilon_{xy} = 0.3$ forward, dotted red line for the case of $\varepsilon_{xy} = 0.3$ backward. The insets
122 show the intensity distributions of the z component of the magnetic field, which correspond to
123 the case of $\varepsilon_{xy} = 0$. As shown in Fig. 2, there are five prominent transmission valleys in each
124 transmission spectrum. For the case of $\varepsilon_{xy} = 0$, five transmission valleys are located at
125 1883.0 nm, 1804.0 nm, 1446.7 nm, 1356.0 nm, 1217.5 nm, respectively. For two-dimensional
126 finite-element modeling, the resonances of the disc cavity are characterized by two integers
127 (m_i, n_i) that count the radial and azimuthal antinode. According to the intensity distributions
128 of the z component of the magnetic field shown in the insets, the five transmission valleys
129 induced by resonant modes are: $TM_{0,0}$, $TM_{0,3}$, $TM_{0,4}$, $TM_{1,1}$ and $TM_{0,5}$. In this paper, we
130 focused mainly on the transverse magneto-optical effect of SPPs, and so the resonant modes:
131 $TM_{0,3}$, $TM_{0,4}$ and $TM_{0,5}$ were researched in detail.

Fig. 3 The transmission spectra, wavelength splitting, IR and IL in mode $TM_{0,5}$. **a, b** The transmission spectra of light from different propagation directions coupled into the disc cavity having different ϵ_{xy} . **c, d** The linear graphs of wavelength splitting, IR, and IL as a function of ϵ_{xy} .

Initially, the isolation performance of the optical isolator structure of resonant mode $TM_{0,5}$ was studied. Fig. 3a and Fig. 3b show the transmission spectra of the optical isolator structures of the resonant mode $TM_{0,5}$ with different ϵ_{xy} . Without any magnetic field, the transmission valley is located at about 1217.5 nm. On applying the magnetic field, the transmitted valley has a red-shift as the SPP traveled forward and a blue-shift almost symmetrically as the SPP traveled backward. Thus, the splitting of forward and backward resonant valleys was observed. With the increase in the value of magneto-optical parameter ϵ_{xy} , the wavelength shifted and the splitting increased. Fig. 3c shows the curve of the splitting of forward and backward resonant valleys varying with the magneto-optical parameter ϵ_{xy} . As shown in Fig. 3c, the splitting is practically positively related to the magneto-optical parameter ϵ_{xy} . Fig. 3d displays the IR and the IL of the optical isolator structure of resonant mode $TM_{0,5}$ for different ϵ_{xy} . With the increase in the value of ϵ_{xy} , both the forward and

backward IL decreased. Besides, when $\varepsilon_{xy} \geq 0.04$, the IL were as small as about 2 dB and remained stable. This means that the forward and backward resonant valleys were entirely separated from each other. The forward and backward isolations exhibited different change curves as the ε_{xy} increased. The forward IR initially decreased and then increased, while the backward IR kept decreasing. As shown in Fig. 3d, we get the maximum IR is greater than 40 dB with a corresponding IL of about 2 dB. The IR was determined using the depth of the transmission valley. It depends on the coupling distance between the MIM waveguide and the disc cavity. So, the IR can be fine-tuned by changing the gap between the MIM waveguide and the disc cavity, g . The relevant results show that the large magneto-optical effect exists in the optical isolator structure presented herein, and as a result, a high-performance on-chip integrated optical isolator is obtained.

159

160 **Fig. 4** Line graph of the $\Delta\lambda/\lambda$ ratio varying with ε_{xy} for different modes. The insets are the partially
 161 enlarged view of data points when $\varepsilon_{xy} = 0.2$ and $\varepsilon_{xy} = 0.3$

Subsequently, the enhancement of transverse magneto-optical effect by the coin paradox SOI was studied in detail. As mentioned above, the enhancement of transverse magneto-optical effect by the coin paradox SOI will be more significant for smaller azimuthal mode number n . The simulation results were used to prove this law. As shown in Figure 2, for the cases of $TM_{0,5}$, $TM_{0,4}$ and $TM_{0,3}$, the splitting $\Delta\lambda$ increased with the decrease in the azimuthal mode number n . To accurately compare the intensity of the transverse magneto-optical effects of different modes, line graphs of the $\Delta\lambda/\lambda$ ratio varying with ε_{xy} for different modes are plotted in Figure 4. As shown in Figure 4, for three different modes, $\Delta\lambda/\lambda$ ratio just has a slight change. Besides, as shown in the insets, $\Delta\lambda/\lambda$ ratios of $TM_{0,5}$ and $TM_{0,4}$ are almost the same and that of $TM_{0,3}$ is the largest. These simulation results are contrary to the theory reported in Ref. [26]. For the cases of $TM_{0,5}$, $TM_{0,4}$ and $TM_{0,3}$, the resonance wavelength increased with the decrease in the azimuthal mode number n , which is clearly shown in Figure 2. As the wavelength increased, the absolute value of the metal's dielectric permittivity ε_M increased rapidly, resulting in a decrease in β_{SPP} . According to the theory in Ref. [26], the transverse magneto-optical effect was expected to be weakened, and the $\Delta\lambda/\lambda$ ratio to be smaller. Therefore, the present simulation results are contrary to the theory in Ref. [26]. The enhancement in the transverse magneto-optical effect by the coin paradox SOI can solve this contradiction between the simulation results and the theory in Ref. [26]. As mentioned above, the coin paradox SOI is more significant for smaller azimuthal mode number n . So, enhancing the transverse magneto-optical effect by the coin paradox SOI is also more significant for smaller n . Thus, the enhancement in the transverse magneto-optical effect by the coin paradox SOI cancels or even overtakes the weakening triggered by the increase in wavelength. In addition, another conclusion can be drawn that the abnormally large transverse magneto-optical effect mentioned in this work is caused by the coin paradox SOI and remains strong in a large wavelength range.

Fig. 5 The transmission spectra and wavelength splitting of the disc cavity with different radii. **a** The transmission spectra of light from different propagation directions are coupled into a disc cavity with different radii. The insets correspond to the intensity distribution of the z component of the magnetic field when $\epsilon_{xy} = 0$. **b** Linear graph of wavelength splitting for disc cavity with different radii

For smaller azimuthal mode number n , the enhancement of the transverse magneto-optical effect by the coin paradox SOI is more significant. Therefore, a smaller cavity will have a greater transverse magneto-optical effect in the same wavelength range, that is, a greater wavelength splitting. To confirm this conclusion, the radius of disc cavity R was set to a smaller value, 410 nm. The transmission spectrum of smaller cavity $R=410$ nm is shown in Figure 5a, and compared to that of bigger cavity $R=500$ nm. It can be seen that $TM_{0,4}$ for smaller cavity $R=410$ nm and $TM_{0,5}$ for bigger cavity $R=500$ nm are both located at about 1217 nm. The linear graph of wavelength splitting changing with the ϵ_{xy} for different radii of disc, cavity is plotted in Figure 5b. It is obvious that the wavelength splitting of the smaller cavity is larger than that of the bigger cavity, which agrees with our expectations. Moreover, the enhancement of the transverse magneto-optical effect by the coin paradox SOI is proven again. It's well known that with the decrease of the radius of the disc cavity, the full width at half maxima (FWHM) of the spectral line will increase. Bigger FWHM has been the main insurmountable sticking point that hinders the application of cavities with smaller model volumes. The change in FWHM induced by the change of the ϵ_{xy} can be ignored. With the

207 radius of the disc cavity decreasing from 500 nm to 410 nm, the FWHM increased from about
208 7.210 nm to about 7.603nm. With the decrease in the radius of the disc cavity, the FWHM
209 increased by about 0.393 nm. This linear expansion can be effectively compensated by
210 increased splitting. For instance, when $\varepsilon_{xy} = 0.1$, the increase in wavelength splitting was
211 about 0.590 nm. When $\varepsilon_{xy} = 0.3$, the increase in wavelength splitting was about 1.689 nm,
212 much greater than 0.393 nm. Therefore, the optical isolator structure presented here, has a
213 greater application potential at a smaller size and is more conducive to a higher degree of
214 optical integration.

215 **Conclusion**

216 In summary, a simple on-chip integrated optical isolator composed of a MIM waveguide and a
217 disc cavity filled with magneto-optical material was designed. In this optical isolator structure,
218 novel coin paradox spin-orbit interaction exists, enhancing the transverse magneto-optical
219 effect effectively. Moreover, the enhancement is more significant for smaller azimuthal mode
220 number n . Based on the enhanced transverse magneto-optical effect, a high-performance on-
221 chip integrated optical isolator was obtained. The maximum IR was found to be greater than 40
222 dB with IL of about 2 dB. The transverse magneto-optical effect remains strong in a wide
223 wavelength range. Furthermore, the greater transverse magneto-optical effect of the smaller
224 cavities is verified, which can surmount the broadening of the resonance valleys induced by the
225 smaller cavity effectively.

226 227 **Abbreviations**

228 MIM: Metal-Insulator-Metal; SOI: Spin-orbit interaction; IR: isolation ratio; IL: insertion loss; SPP: Surface plasmon
229 polariton; TSAM: Transverse spin angular momentum; LSAM: Longitudinal spin angular momentum; OAM: Orbital
230 angular momenta; TM: Transverse magnetic; Bi: YIG: Bismuth-doped Yttrium Iron Garnet; FEM: finite element
231 method; FWHM: Full width at half maxima.

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233 Not application.

234 **Authors' contributions**

HH conceived the study, carried out the fabrication of the model, the simulation and analysis, and drafted the manuscript. JWQ and QW participated in the transmission spectra analysis and discussion, and revised the manuscript. XHF, HJW, SHZ, ZQC, JC, JHY and XYY participated in the simulation. JJX and QS are the PIs of the project and participated in the design and coordination of the study. All authors read and approved the final manuscript.

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Availability of data and materials

All data supporting the conclusions of this article are included within the article.

Declaration

Competing interests

The authors declare that they have no competing interests.

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