Magneto-optical effects on the properties of the photonic spin Hall effect owing to the defect mode in photonic crystals with plasma

Y. L. Liu, W. C. Chen, and B. Guo

ARTICLES YOU MAY BE INTERESTED IN

Surface kinetics analysis by direct area measurement: Laser assisted dehydration of α-FeOOH
AIP Advances 9, 075101 (2019); https://doi.org/10.1063/1.5092800

High sensitive sensing by a laser diode with dual optical feedback operating at period-one oscillation
Applied Physics Letters 115, 011102 (2019); https://doi.org/10.1063/1.5098811

Brillouin optomechanics in nanophotonic structures
APL Photonics 4, 071101 (2019); https://doi.org/10.1063/1.5088169
Magneto-optical effects on the properties of the photonic spin Hall effect owing to the defect mode in photonic crystals with plasma

Cite as: AIP Advances 9, 075111 (2019); doi: 10.1063/1.5094664
Submitted: 4 March 2019 • Accepted: 9 July 2019 •
Published Online: 17 July 2019

Y. L. Liu, W. C. Chen, and B. Guo

AFFILIATIONS
Department of Physics, Wuhan University of Technology, Wuhan 430070, China

binguo@whut.edu.cn (B. Guo)

ABSTRACT
In this study, we have demonstrated a multi-layered structure to examine how the magneto-optical effects affect the behavior of the photonic spin Hall effect (PSHE). The Faraday and Voigt effects are taken into account. The multi-layered structure is one-dimensional (1D) photonic crystal (PC) with a defective plasma layer. The properties of the PSHE in both symmetric and asymmetric defective PCs are explored. The numerical results show that the applied magnetic field and the geometries of the structures have significantly changed the characteristics of the PSHE. The transverse displacements of the H-polarization can be easily enhanced by more than ten times, while the transverse displacement of the V-polarization can be easily suppressed by a few percent based on the manipulating of the external magnetic field. Moreover, the magneto-optical effects can change the optimal incident angle for the assessment of the peak transverse displacements of the PSHE. In addition, the numerical results also show that the plasma frequency, defective plasma thickness, and the geometry of the structure have greatly influenced the behavior of the PSHE. The parameter dependencies of these effects are also calculated and discussed.

© 2019 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5094664

I. INTRODUCTION
The study of the interplay of electromagnetic waves with plasma has developed into one of the most rapidly growing fields of plasma physics during the last decade. Plasma photonic crystals (PCs)\(^1\)–\(^17\) and plasma metamaterials\(^18\)–\(^20\) are the two outstanding areas pertaining to the use of plasma in the fields of optics and photonics. Compared with conventional PCs and metamaterials, plasma PCs and plasma metamaterials can enable the realization of a tunable device with tunable plasma characteristics based on the control of exogenous factors, such as the applied voltage, gas pressure, temperature, and the external magnetic field.\(^2\) Many artificial systems have been designed based on plasma to study many interesting electromagnetic phenomena, such as the band-gap,\(^21\)\(^2\) negative refraction,\(^23\) surface plasmon,\(^24\) and slow light effects.\(^25\)

Recently, researchers find that there is a transverse splitting of left- and right-handed circularly polarized components when a linearly polarized light passes through an interface with a refractive index gradient. This interesting transport phenomenon was first proposed by Onoda et al.\(^28\) and it is now referred to as the photonic spin Hall effect (PSHE) of light. The reason for the PSHE is attributed to a spin-orbital interaction.\(^29\) Because the PSHE can provide new opportunities for the control of photons to develop spin-controlled nanophotonic devices, it may have many unique and interesting potential applications. However, the phenomenon of the PSHE yields very weak responses because the transverse displacements are at the subwavelength scale. It is difficult to detect these transverse displacements directly using normal experimental equipment. Despite that weak measurement method\(^29\) have been adopted for the successful experimental observation of the PSHE, enhancing the transverse displacements is still an important issue. In addition, the PSHE sometimes needs to be suppressed. Many architectures have been proposed to develop the applications based on the PSHE.\(^30\)–\(^40\) In previous studies,\(^34\)–\(^36\) it was concluded that the
magnitudes of the transverse displacements mainly depended on the ratio \( |r_p|/|r_f| \) or \( |r_s|/|r_r| \) when other quantities were constant for a specific incident angle (herein, \( r_p \) and \( r_f \) are the Fresnel reflection coefficients for s- and p-waves, respectively). Therefore, one can control the properties of the PSHE by increasing or decreasing the ratio \( |r_p|/|r_f| \) or \( |r_s|/|r_r| \). There are two main methods used to realize it at present. One is the Brewster angle effect,\(^{34–36}\) and the other is the surface plasmon resonance effect.\(^{41,42}\) The one-dimensional (1D) PC is a simple multi-layered structure and can be fabricated easily. Moreover, a perfect binary 1D PC (also known as the Bragg reflec-
tor) with a defective layer can often create two sharp and narrow polarization-dependent reflection valleys for \( s \)- and \( p \)-waves, respectively. Therefore, one can control the properties of the PSHE by increasing or decreasing the ratio \( |r_p|/|r_f| \) or \( |r_s|/|r_r| \) when other constitutive parameters are chosen. As a result, the PSHE is either enhanced (owing to the increased values of the first ration \( |r_p|/|r_f| \)) or suppressed (owing to the increased values of the second ratio \( |r_s|/|r_r| \)). In this study, we have demonstrated a multi-layered structure to study the properties of the PSHE. The basic structure is PC in 1D with a defective plasma layer. Herein, two defective PCs stacked in symmetric and asymmetric geometries are thus examined. It is well known that there are two well-known magneto-optical effects,\(^{3} \) that is, the Faraday and Voigt effects, that are evoked when the proposed structure is exposed to an external magnetic field. There are also two modes in this configuration, the right-circular polarization (RCP) and the left-circular polarization (LCP). In addition, in the case of the Voigt effect, the propagation direction of incident light is parallel to the external magnetic field. There are two modes in this configuration, the regular (O) and the extraordinary (E) waves. The dielectric function of the plasma after its exposure to an external magnetic field can be expressed as:\(^{14}\)

\[
\mathbf{E}_D = \begin{cases} 
LCP & \left(1 - \omega_D^2 \left( \omega (\omega + \omega_{ce}) \right) \right), \\
RCP & \left(1 - \omega_D^2 \left( \omega (\omega - \omega_{ce}) \right) \right), \\
O & \left(1 - \omega_D^2 \left( \omega^2 - \omega_{ce}^2 \right) \right) / \left( \omega^2 (\omega^2 - \omega_{ce}^2 - \omega_{ce}^2) \right), 
\end{cases}
\]

where \( \omega_D \) is the bulk plasma frequency, \( \omega \) is the frequency of incident light which depends on the designed wavelength \( \lambda_0 \), and \( \omega_{ce} = eB/m_e c \) is the cyclotron frequency. Herein, \( B \) is the amplitude of the external magnetic field, \( e \) and \( m_e \) are the absolute change and effective mass of the electron, and \( c \) is the velocity of light in free space. From Eq. (1), one can observe that the applied magnetic field has no effect on the dielectric function of plasma in the case of the ordinary mode. Therefore, we neglect this mode in this study.

When a linearly polarized light is incident obliquely on the stacked defective PC, it is reflected at the air-PC interface. Herein, we studied the PSHE of this reflected light. To calculate the transverse displacements, one first assumed that the incident light was Gaussian beam, and then expressed the incident beam as the sum or difference of horizontal and vertical components in the spin basis set. Finally, the expressions of spin-dependent shifts of reflected light is used to calculate the transverse displacements. After straightforward
calculated, the transverse displacements of H- and V-polarization can be expressed as:

\[
\Delta_{H}^\nu = \frac{1}{k + \partial \theta \rho / (k w_0^2 \rho^2)} \cot \theta \frac{1 \pm |r_1| |r_2|}{|r_1| + 2 |r_2|} \cos (\phi_i - \phi_p) \cot \theta_i, \tag{2}
\]

\[
\Delta_{V}^\nu = \frac{1}{k + \partial \theta \rho / (k w_0^2 \rho^2)} \cot \theta \frac{1 \pm |r_1| |r_2|}{|r_1| + 2 |r_2|} \cos (\phi_i - \phi_p) \cot \theta_i, \tag{3}
\]

where

\[
\alpha_H = \frac{1}{k w_0^2} \left(1 + \frac{|r_1|^2}{|r_2|} + \frac{2 |r_1|}{|r_2|} \cos (\phi_i - \phi_p) \right) \cot^2 \theta_i, \tag{4}
\]

\[
\alpha_V = \frac{1}{k w_0^2} \left(1 + \frac{|r_1|^2}{|r_2|} + \frac{2 |r_1|}{|r_2|} \cos (\phi_i - \phi_p) \right) \cot^2 \theta_i, \tag{5}
\]

where \( r_{p,s} = |r_{p,s}| \exp(i \phi_{p,s}) \) are the phases of the Fresnel reflection coefficients \( r_{p,s} \), and \( w_0 \) is the waist of the incident Gaussian beam. Eqs. (2) and (3) are first-order results of the transverse displacements. In fact, comparing these with \( k + \partial \theta \rho / (k w_0^2 \rho^2) \), \( \alpha_H, \alpha_V \) are much smaller and can be ignored, in a similar manner to many previous studies.

According to the transfer matrix method, the Fresnel reflection coefficients \( r \) can be described as

\[
r = \frac{M_{21}}{M_{11}}, \tag{6}
\]

where \( M_{11} \) and \( M_{21} \) are the two matrix elements of the following total transfer matrix \( M \) written by

\[
M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}. \tag{7}
\]

The total system matrix for symmetric PC is given by

\[
M_{\text{sym}} = (D_0)^{-1} \left[ D_A P_A (D_A)^{-1} D_B P_B (D_B)^{-1} \right]^N \tag{8}
\]

\[
[ D_B P_B (D_B)^{-1} ] \left[ D_A P_A (D_A)^{-1} D_B P_B (D_B)^{-1} \right] D_B, \tag{9}
\]

where the propagation matrix in Eq. (6) for layer \( i (i = A, B, D) \) is given by

\[
P_i = \begin{pmatrix} \exp(- j k_i^z d_i) & 0 \\ 0 & \exp(j k_i^z d_i) \end{pmatrix}. \tag{10}
\]

As for the asymmetric defective PC, the total system matrix is given by

\[
M_{\text{asym}} = (D_0)^{-1} \left[ D_A P_A (D_A)^{-1} D_B P_B (D_B)^{-1} \right]^N \left[ D_B P_B (D_B)^{-1} \right] \left[ D_A P_A (D_A)^{-1} D_B P_B (D_B)^{-1} \right] D_B, \tag{11}
\]

From Eqs. (6) and (10), the matrix elements \( M_{11} \) and \( M_{21} \) can be easily obtained. Thus, the Fresnel reflection coefficients \( r_{p,s} \) can be calculated by Eq. (5). Substituting \( r_{p,s} \) in Eqs. (2) and (3), one can get the transverse displacements of the H- and V-polarizations.

III. RESULTS AND DISCUSSION

In this section, the numerical calculations of Eqs. (2) and (3) are presented. The selective parameters are chosen as follows: the operation wavelength is \( \lambda_0 = 632.8 \text{nm} \), the refractive index values are \( n_A = 1.337 \) and \( n_B = 2.351 \), the thickness values are \( d_A = 115 \text{nm} \) and \( d_B = 68 \text{nm} \), the periodical number is set to \( N = 2 \) and the beam waist is \( w_0 = 30 \lambda_0 \). It is easy to notice that each horizontal and vertical transverse displacement has two opposite values from Eqs. (2) and (3). Therefore, only the positive values of the transverse displacements are plotted in the study for simplicity of the construction of the figure. Moreover, the transverse displacements for both the horizontal and vertical polarizations are normalized to the designed wavelength of the incident light \( \lambda_0 \).

Figures 2 and 3 present the effect of the applied magnetic field on the transverse displacements for two different polarizations. The transverse displacement of H-polarization is shown in Fig. 2, the transverse displacement of V-polarization is shown in Fig. 3. Herein, the plasma frequency is set to \( \omega_p = 0.5 \omega_0 \) and the defective plasma thickness is set to \( d = 300 \text{nm} \). It is clear to see that in both cases, the existence of the external magnetic field has greatly changed the peak transverse displacements. However, the way of the influences are quite different. For the transverse displacement of the H-polarization in both the symmetric and asymmetric geometries, the peak transverse displacements can be enhanced as a function of the strength of the applied magnetic field, and are increased in the case of the LCP mode (see Fig. 2(a) and Fig. 2(d)). Specifically, in the case of the symmetric geometry, they can reach values that exceed the designed wavelength by more than ten times. In addition, the optimal incident angles of the peak transverse displacements are nearly the same. The differences are small. By contrast, in the case of the RCP and extraordinary modes, increases of the strength of applied magnetic field cause decreases of the peak transverse displacements. Moreover, the optimal incident angle for the peak transverse displacement is quite different. It moves to regions with lower angles when the strength of the applied magnetic field is increased, especially in the case of symmetric geometries (see Fig. 2(b) and Fig. 2(c) for RCP mode). The same phenomena apply in the asymmetric geometry case (see Fig. 2(e) and Fig. 2(f) in the case of the extraordinary mode). However, it is not so obvious when the outcomes compared with those evoked in the symmetric geometry case. It should be noted that the enhanced transverse displacements of the H-polarization is sharp and narrow in these three modes in the case of symmetric geometry. This is an interesting finding and can be useful to develop some potential applications. Compared to the enhancement of the transverse displacements of the H-polarization, the transverse displacements
FIG. 2. Transverse displacement of the reflection beam for H-polarization as a function of incident angle $\theta$ for different applied magnetic fields in three modes, including the (a, d) left-circular polarization (LCP), (b, e) right-circular polarization (RCP), and (c, f) extraordinary modes. Herein, a, b, and c are plotted for the symmetric defective PC, while d, e, and f are plotted for the asymmetric defective PC.

of the V-polarization are suppressed in these modes, even by a few percent of the value of the designed wavelength (see Fig. 3(a) and Fig. 3(d) in the case of the LCP mode). The transverse displacements of the V-polarization increase as a function of the strength of applied magnetic field in the case of the symmetric geometry, while they decrease in the asymmetric geometry, as shown in Fig. 3(b)–(c) in the case of the RCP mode, and in Fig. 3(e)–(f) in the case of the extraordinary mode. However, the transverse displacements of the H-polarization increase with increases a function of the strength of the applied magnetic field in both the symmetric and asymmetric geometries for both the RCP and extraordinary modes. In addition, one can observe that the phenomena of the PSHE disappear when the external magnetic field is manipulated, as shown in the case of $\omega ce = 0.7\omega$ in Fig. 2(e)–(f). In fact, as long as the strength of the applied magnetic field is large enough, the phenomena of the PSHE will disappear in the cases of both the RCP and extraordinary modes, irrespective of whether symmetric or asymmetric geometries are considered.

Similar to our previous study, the effects of plasma frequency and defective plasma layer thicknesses are also examined in this study. Here, the numerical results of the optimal incident angle and the correspondingly peak values of transverse displacements are presented in the table format, see Tables I and II.

Table I gives the results of the effect of plasma frequency on the behavior of the PSHE. The external magnetic field is chosen as $\omega ce = 0.7\omega$ and the defective layer thickness is chosen as $d = 300$nm. As shown in Table I, it is clear to see that the transverse displacements of H-polarization can be greatly enhanced for all different plasma frequencies in the LCP mode for asymmetric geometry. However, the transverse displacement of H-polarization is enhanced for smaller plasma frequency while is suppressed for higher plasma frequency (see the case of $\omega p = 0.8\omega$ in the LCP mode). In the RCP mode, for both symmetric and asymmetric geometries, only the case of smaller plasma frequencies can lead to huge transverse displacements of H-polarization, see the case of $\omega p = 0.2\omega$. The case of the extraordinary mode has similar behavior as the case of the RCP mode. However, it is worth noting that a huge
FIG. 3. Transverse displacement of the reflection beam for V-polarization as a function of incident angle $\theta$ for different magnetic fields in three modes, including the (a, d) LCP mode, (b, e) RCP mode, and (c, f) extraordinary modes. Herein, a, b, and c are plotted for the symmetric defective PC; while d, e, and f are plotted for the asymmetric defective PC.

TABLE I. Optimal results of the transverse displacements for both H- and V-polarizations in three modes with the effect of plasma frequency. Here, $x$ denotes the optimal incident angle and $y$ denotes the peak value of transverse displacement of the photonic spin Hall effect in the bracket $(x, y)$ of Table I. The unit of $x$ is degree and $y$ is dimensionless quantity which is normalized as the wavelength of incident light $\lambda_0$.

| Case $\Delta^H$ | LCP mode | RCP mode | Extraordinary mode |
|-----------------|-----------|-----------|---------------------|
| $\omega_p = 0.2\omega$ | (44, 12.67) | (66, 14.02) | (41, 12.20) | (64, 13.46) |
| $\omega_p = 0.4\omega$ | (42, 9.29) | (63, 13.29) | (22, 0.30) | (42, 5.54) | (29, 0.72) | (49, 7.95) |
| $\omega_p = 0.6\omega$ | (37, 2.41) | (58, 11.20) | (78, 0.03) | (78, 0.03) | (26, 0.07) | (73, 0.06) |
| $\omega_p = 0.8\omega$ | (30, 0.75) | (50, 8.02) | (81, 0.02) | (81, 0.02) | (29, 0.03) | (79, 0.03) |

| Case $\Delta^V$ | LCP mode | RCP mode | Extraordinary mode |
|-----------------|-----------|-----------|---------------------|
| $\omega_p = 0.2\omega$ | (43, 0.67) | (69, 0.08) | (39, 0.26) | (63, 0.10) | (41, 0.29) | (66, 0.09) |
| $\omega_p = 0.4\omega$ | (41, 0.28) | (66, 0.09) | (21, 0.17) | (42, 0.18) | (29, 0.21) | (50, 0.14) |
| $\omega_p = 0.6\omega$ | (36, 0.23) | (59, 0.11) | (78, 0.03) | (78, 0.03) | (79, 0.03) | (79, 0.03) |
| $\omega_p = 0.8\omega$ | (29, 0.21) | (50, 0.14) | (81, 0.02) | (81, 0.02) | (26, 0.06) | (73, 0.06) |
transverse displacement of H-polarization can be realized for the case of the extraordinary mode for the asymmetric structure, see the case of $\omega_p = 0.8\omega$. The optimal incident angles for huge transverse displacements is quite different for symmetric and asymmetric geometries. The influence of symmetric geometry is obvious, while the influence of asymmetric geometry is small for all three modes. Compared with the enhanced transverse displacements of H-polarization, the transverse displacements of V-polarization are significantly suppressed. In the case of the LCP mode, the peak transverse displacement for the symmetric geometry is negatively related to the plasma frequency. However, it is positively related to plasma frequency for the asymmetric geometry. In addition, we also found that the optimal incident angles shift to lower region with the increasing of plasma frequency. In the cases of the RCP and the extraordinary modes for symmetric geometry, the larger transverse displacement of V-polarization can be obtained for smaller plasma frequency, see the case of $\omega_p = 0.2\omega$. However, in the asymmetric geometry, the law is invalid. From the Table I, it is can be easily concluded that huge displacements can be realized in the LCP modes for all plasma frequency, but only for low plasma frequency in the RCP mode. For the extraordinary mode, both low and high plasma frequencies can make larger transverse displacements, while it cannot be realized in the case of intermediate plasma frequency.

Table II presents the results of the effect of plasma thickness on the properties of the PSHE. The parameters are selected as plasma frequency $\omega_p = 0.5\omega$ and the applied magnetic field $\omega_c = 0.7\omega$. It can be seen from the Table II that the bigger defective plasma thickness can lead to huge transverse displacements of H-polarization for all three modes, see the case of $d = 320$nm. Especially, the phenomenon is very obvious for both cases of the LCP and RCP modes for symmetric geometry. It can be concluded that the huge transverse displacements of H-polarization can be realized easily in these two cases. Also, the effect of the defective layer thickness is more sensitive in the case of symmetric geometry than in the case of asymmetric geometry. Since the transverse displacements of V-polarization are greatly suppressed and are small, the influence of defective layer thickness is not as sensitive as for the transverse displacements of H-polarization. Moreover, other behavior of transverse displacements of V-polarization are similar to the H-polarization. In addition, the effect of defective layer thickness on the optimal incident angles for the bigger transverse displacements is slightly, especially for the asymmetric geometry.

**IV. CONCLUSIONS**

In conclusion, we have investigated the magneto-optical effects on the properties of the PSHE with the use of a simple multi-layered structure. The multi-layered structure was engineered in the forms of symmetric and asymmetric defective PCs. The transverse displacements of H- and V-polarizations are calculated. The transverse displacements of the H-polarizations can be enhanced significantly while the transverse displacement of V-polarization can be suppressed considerably. The phenomena of the PSHE can vanish by increasing the strength of the applied magnetic field in both the symmetric and asymmetric geometries. The magneto-optical effects on the optimal incident angles for peak transverse displacements of both the H- and V-polarizations were also discussed. Due to the magneto-optical effect, including the Faraday and Voigt effects, the properties of the PSHE is tunable. Moreover, the plasma frequency and the defective plasma thickness can influence the properties of the PSHE. In addition, the geometry of the proposed defective PC also lead to a different PSHE behavior, and can be considered as an effective regulation method. The method proposed in this paper can be easily realized and can be used to guide the experiments and fabrication of the spin-based nanophotonic devices. The results can pave the way toward the development of spin-based photonic devices based on the PSHE in the future.

**ACKNOWLEDGMENTS**

This work was supported by the Natural Science Foundation of China (NSFC) (11575135).

**REFERENCES**

1. H. Hojo and A. Mase, *Journal of Plasma Fusion Research* **80**, **89** (2004).
2. O. Sakai, T. Sakaguchi, and K. Tachibana, *Applied Physics Letters* **87**, 241505 (2005).
3. O. Sakai, T. Sakaguchi, and K. Tachibana, *Contributions to Plasma Physics* **47**, 96 (2007).
B. Guo, *Physics of Plasmas* **16**, 043508 (2009).

B. Guo, *Plasma Science and Technology* **11**, 18 (2009).

W. L. Fan and L. F. Dong, *Physics of Plasmas* **17**, 073506 (2010).

H. F. Zhang, S. B. Liu, X. K. Kong, L. Zou, C. Z. Li, and W. S. Qing, *Physics of Plasmas* **19**, 022103 (2012).

L. Qi, C. Li, G. Fang, and X. Gao, *Plasma Science and Technology* **17**, 4 (2015).

T. F. Khalkhali and A. Bananej, *Journal of Modern Optics* **64**, 830 (2016).

G. Lehmann and K. H. Spatschek, *Physical Review Letters* **116**, 225002 (2016).

B. Wang and M. A. Cappelli, *Applied Physics Letters* **108**, 161101 (2016).

H. F. Zhang and S. B. Liu, *AIP Advances* **6**, 085116 (2016).

S. K. Awasthi, R. Panda, and L. Shiveshwari, *Physics of Plasmas* **24**, 072111 (2017).

G. Lehmann and K. H. Spatschek, *Physics of Plasmas* **24**, 056701 (2017).

H. Tan, C. Jin, L. Zhuge, and X. Wu, *IEEE Transactions on Plasma Science* **46**, 539 (2018).

H. F. Zhang and Y. Q. Chen, *Physics of Plasmas* **24**, 042116 (2017).

N. Pourali and H. Bahador, *Physics of Plasmas* **26**, 013515 (2019).

S. Osamu and T. Kunihide, *Plasma Sources Science and Technology* **21**, 013001 (2012).

B. Guo, *Chinese Physics Letters* **30**, 105201 (2013).

Y. Zhan and B. Guo, *Plasma Science and Technology* **21**, 015002 (2019).

B. Guo, M. Q. Xie, and L. Peng, *Physics of Plasmas* **19**, 072111 (2012).

B. Guo, M. Q. Xie, X. M. Qiu, and L. Peng, *Physics of Plasmas* **19**, 044505 (2012).

B. Guo, *Physics of Plasmas* **20**, 093508 (2013).

B. Guo, *Physics of Plasmas* **20**, 093506 (2013).

F. Feng, M.-H. Lu, V. Lomakin, and Y. Fainman, *Applied Physics Letters* **93**, 231105 (2008).

A. W. Zeng and B. Guo, *Optical and Quantum Electronics* **49**, 200 (2017).

A. W. Zeng, M. X. Gao, and B. Guo, *Applied Physics B* **124**, 146 (2018).

M. Onoda, S. Murakami, and N. Nagaosa, *Physical Review Letters* **93**, 083901 (2004).

O. Hosten and P. Kwiat, *Science* **319**, 787 (2008).

X. Ling, X. Zhou, K. Huang, Y. Liu, C. W. Qiu, H. Luo, and S. Wen, *Reports on Progress in Physics* **80**, 066401 (2017).

Y. Liu, Y. Ke, H. Luo, and S. Wen, *Nanophotonics* **6**, 51 (2017).

A. Aiello, N. Lindlein, C. Marquardt, and G. Leuchs, *Physical Review Letters* **103**, 100401 (2009).

T. Tang, J. Li, Y. Zhang, C. Li, and L. Luo, *Optics Express* **24**, 28113 (2016).

H. Luo, X. Zhou, W. Shu, S. Wen, and D. Fan, *Physical Review A* **84**, 043806 (2011).

C. Gao and B. Guo, *Physics of Plasmas* **24**, 093520 (2017).

X. Ling, H. Luo, M. Tang, and S. Wen, *Chinese Physics Letters* **29**, 074209 (2012).

X. Zhou, X. Ling, H. Luo, and S. Wen, *Applied Physics Letters* **101**, 251602 (2012).

W. Zhu and W. She, *Optics Letters* **40**, 2961 (2015).

H. Zheng, C. Gao, M. Gao, and B. Guo, *Optical and Quantum Electronics* **50**, 273 (2018).

J. Li, T. Tang, L. Luo, and J. Yao, *Carbon* **134**, 293 (2018).

X. Zhou and X. Ling, *IEEE Photonics Journal* **8**, 1 (2016).

P. S. Pershan, *Journal of Applied Physics* **38**, 1482 (1967).

V. L. Ginzberg, *The Propagation of Electromagnetic Waves in Plasmas* (Pergamon, New York, 1970).

M. Cheng, P. Fu, X. Tang, S. Chen, X. Chen, Y. Lin, and S. Feng, *Journal of the Optical Society of America B* **35**, 1829 (2018).

P. Yeh, *Optical Waves in Layered Media* (John Wiley and Sons, Singapore, 1991).

W. Chen, Y. Liu, and B. Guo, *Physics of Plasmas* **26**, 052110 (2019).