Coupling-Mediated Selective Spin-to-Plasmonic-Orbital Angular Momentum Conversion

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Orbital angular momentum (OAM) has been recently introduced to plasmonics for generating plasmonic vortices with a helical wavefront, opening avenues for exotic on-chip applications such as quantum information processing and communications. In previous demonstrations, carefully designed optical elements are used to convert left- and right-circular polarizations into plasmonic vortices with different topological charges, resulting in conversion from optical spin angular momentum (SAM) to plasmonic OAM. Here, it is demonstrated theoretically and experimentally that by utilizing the near-field coupling between paired resonators in a metasurface, selective conversion from optical SAM to plasmonic OAM is realized, where generation of plasmonic vortices can be achieved for incident light of one circular polarization while significantly suppressed for the other circular polarization. The proposed design scheme may motivate the design and fabrication of future practical plasmonic devices.

Light carries coordinate-independent spin angular momentum (SAM)^[1] of $\pm\hbar$ per photon, corresponding to left- and right-circular polarizations (LCP and RCP), where $\hbar$ is the reduced Planck's constant. In the pioneering work by Allen et al.,^[2] it was shown that electromagnetic fields with a phase profile $e^{il\theta}$ could also carry orbital angular momentum (OAM), where l and θ are the topological charge and azimuth angle, respectively. Such beams, known as optical vortices, rotate around

their axis of propagation like a corkscrew, and possess a “doughnut” intensity profile.^[3] In the past few decades, many demonstrations and applications of vortex beams have been reported, including optical data storage,^[4,5] optical tweezers,^[6] quantum cryptography,^[7] communications,^[8,9] etc. Particularly, geometric phase devices composed of basic elements with a spatially varying orientation could perform spin-to-orbital angular momentum conversion,^[10–14] providing a direct connection between optical SAM and OAM.^[15]

Recently, plasmonic vortices generated through excitation of surface plasmons (SPs) with azimuthal-dependent phase profiles $e^{il\theta}$ at a metal-dielectric interface have attracted considerable attention^[16–22] due to their strong OAM in the evanescent field region. In particular, Archimedean spirals^[16–18,22] and well-arranged subwavelength resonators^[19–21] have been employed to achieve spin-to-plasmonic-orbital angular momentum conversion, providing useful insights into the nature of OAM and opening the door toward a number of exciting on-chip applications.^[17,23] In most of these works, the incident LCP and RCP waves were transformed to plasmonic vortices of different topological charges, and the associated spin-dependent phenomena can be regarded as the photonic spin-Hall effect.^[24–26] In direct analogy with the

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Figure 1. Design of selective spin-to-plasmonic-orbital angular momentum conversion. a) Schematic diagram illustrates the designed metasurface and the spin-coded response under different illuminations. b) Scanning electron microscopy image illustrates a part of the fabricated metasurface. Scale bar, 100 μm . c) Enlarged view of an SSR-pair in (b) with defined parameters.

spin-Hall effect in electronic systems,^[27,28] the intrinsic photonic spin-Hall effect was first proposed based on semiclassical treatments on wave-packets of light, where spin-orbital coupling naturally occurs when light travels along a curved trajectory.^[29] However, experiments show that such an effect is extremely weak. Recently, strong photonic spin-Hall effects were extended to the field of metasurfaces by carefully designing subwavelength resonators,^[30–34] which is analogous to the extrinsic spin-Hall effect discovered in electronic systems. In this communication, to further exploit the spin degrees of freedom in plasmonics, selective conversion from optical SAM to plasmonic OAM via coupled plasmonic resonators in a metasurface is theoretically analyzed and experimentally demonstrated. By carefully engineering the near-field interaction between the designed paired resonators, the conversion can be achieved for one spin state while significantly suppressed for the other spin state, as schematically illustrated in **Figure 1a**.

Our metasurface, operating in the terahertz regime, is composed of ring-shape arranged subwavelength meta-molecules, with each meta-molecule consisting of two split-ring-shaped slit resonators (SSRs) oriented along orthogonal directions and positioned in a mirror symmetric configuration. In general,

the spin-dependent phenomenon can hardly be observed in the material whose elements have fourfold rotation symmetry along the propagation axis of light, since such a material is isotropic for the incident light, resulting in a degeneracy of circular polarizations in the momentum space. In the proposed design, the meta-molecule only has twofold rotation symmetry. Furthermore, although the overall structure exhibits rotation symmetry, its in-plane mirror symmetry is broken, providing the possibility for spin dependent behaviors.^[20] A scanning electron microscopy image exhibiting a part of the fabricated sample is shown in **Figure 1b**, which is made from a 200 nm thick aluminum structure patterned on a 2 mm thick quartz substrate using conventional photolithography and metallization processing. **Figure 1c** illustrates a single meta-molecule, the so-called SSR-pair, where $a = b = 44.3 \mu\text{m}$, $w = g = 10 \mu\text{m}$, and $s = 5 \mu\text{m}$. The working frequency of the structure is around 0.75 THz, and the distance s is much less than the corresponding SP wavelength λ_{SP} , thus ensuring near-field coupling between the paired SSRs.

Figure 2a presents a top view schematic of the metasurface, in which 36 SSR-pairs are arranged on a circle with a circumference equal to $18\lambda_{\text{SP}}$, and hence the distance D between the

Figure 2. Theoretical analysis of SP excitation from the SSR-pairs. a,b) Schematic diagrams of the whole range and a single unit of the designed meta-surface, respectively. c) Simulated SP field (the real part of E_z) distribution at 0.75 THz for a single SSR under the y -polarization incidence. The SSR is located at the center with the inset in the top-left corner representing the corresponding orientation. d,e) Simulated amplitude and phase spectra of E_z at positions marked by the red and green dots in (c), respectively.

adjacent SSR-pairs is about $\lambda_{sp}/2$, which is large enough to minimize the coupling between the adjacent SSR-pairs.^[34] As the complementary structure to the well-known metamaterial unit, i.e., the split-ring resonator, the optical response of an SSR has been studied according to the Babinet's principle.^[35,36] The fundamental resonance of an SSR can be excited by either a magnetic field applied perpendicular to the gap or by an electric field passing through the ring.^[36] To analyze the coupled system and to explore the possibility of spin-coded selective conversion, the interaction of light with the n th resonator pair (as shown in Figure 2b) is described by the following equations based on the coupled mode theory^[37–39]

$$\frac{\partial}{\partial t} q_{n-1} = (i\omega_q - \gamma_s - \gamma_a) q_{n-1} + i\kappa q_{n-2} + \chi E_{n-1} \quad (1a)$$

$$\frac{\partial}{\partial t} q_{n-2} = (i\omega_q - \gamma_s - \gamma_a) q_{n-2} + i\kappa q_{n-1} + \chi E_{n-2} \quad (1b)$$

where q_{n-1} and q_{n-2} are the complex resonance amplitudes of the outer resonator R_{n-1} and inner resonator R_{n-2} , respectively.

Since these two resonators are identical, they have the same resonance coefficients including the resonance frequency ω_q , radiation damping γ_s , and absorption damping γ_a . Since the resonators R_{n-1} and R_{n-2} are perpendicularly oriented to each other, the coupling $i\kappa$ between them is only near-field coupling and thus purely imaginary. Furthermore, χ denotes the coupling to the incident fields E_{n-1} and E_{n-2} . Here, γ_s , γ_a , κ , and χ are all real.

In the case of a circular polarization input $E_{in} = \sqrt{2}/2 (1, \sigma i)$, where $\sigma \in \{+, -\}$ corresponds to LCP and RCP, respectively, E_{n-1} and E_{n-2} could be described as

$$E_{n-1} = \frac{\sqrt{2}}{2} e^{i\sigma\theta_n} \quad (2a)$$

$$E_{n-2} = -\frac{\sqrt{2}}{2} \sigma i e^{i\sigma\theta_n} \quad (2b)$$

where θ_n is the orientation angle of the n th SSR-pair with respect to the x -axis (as shown in Figure 2a). Substituting

Equation (2) into Equation (1), at resonance frequency $\omega = \omega_q$, we can calculate q_{n-1} and q_{n-2} as

$$q_{n-1} = \frac{\sqrt{2}}{2} \frac{\chi(\gamma_s + \gamma_a + \sigma\kappa)}{(\gamma_s + \gamma_a)^2 + \kappa^2} e^{i\sigma\theta_n} \quad (3a)$$

$$q_{n-2} = \frac{\sqrt{2}}{2} \frac{\chi[\kappa - \sigma(\gamma_s + \gamma_a)]}{(\gamma_s + \gamma_a)^2 + \kappa^2} ie \quad (3b)$$

where the time harmonic term has been chosen as $e^{i\omega}$. From Equations (3a) and (3b), it is obvious that under the critical condition $\kappa = \gamma_s + \gamma_a$, all the resonance energies are stored in either the outer or inner resonator, depending on the handedness of the incident light. Here, the proposed SSR-pair is a weakly coupled system with $\kappa < \gamma_s + \gamma_a$. Since all the coefficients are real, there is a handedness-dependent phase difference $\arg(q_{n-1}/q_{n-2}) = \sigma\pi/2$. However, in the case of $\kappa > \gamma_s + \gamma_a$, one can easily deduce that the $\pi/2$ phase difference still holds but the handedness dependence is opposite. This $\pi/2$ phase difference can be attributed to the geometric phase resulting from the perpendicular orientation of R_{n-1} and R_{n-2} .

Next, we consider the inward SP excitations that arise from these resonances. As marked by the red rows in Figure 2b, the complex amplitudes of the SP excitation due to the n th SSR-pair, S_{n-1} and S_{n-2} , should be proportional to q_{n-1} and q_{n-2} , respectively, i.e.

$$S_{n-1} = \eta_1 q_{n-1} \quad (4a)$$

$$S_{n-2} = \eta_2 q_{n-2} \quad (4b)$$

where η_1 and η_2 are two complex coefficients. Although it is difficult to analytically calculate η_1 and η_2 since the precise interactions between light and the resonators are quite complicated, the relative relation between η_1 and η_2 can be approximately acquired by comparing the simulated SP excitation for a single SSR. Figure 2c illustrates the corresponding simulated SP field distribution by using commercial software CST Microwave Studio. A y -polarized broadband plane wave is normally incident onto the designed structures from the $-z$ direction to excite the SPs, and the distribution of the E_z field is obtained at 50 μm above the metasurface on the air side. Clearly, both the $\pm x$ and $\pm y$ directional SP excitations can be observed. To compare the excitations, two field probes are placed $2\lambda_{\text{SP}}$ away from the resonator in the $+x$ and $-y$ directions, respectively, as marked by the red and green dots in Figure 2c. The extracted spectra are presented, respectively, in Figure 2d,e to show the amplitude and phase differences at these two positions. Through the relation $Ae^{i\varphi} = \eta_1/\eta_2$ with A and φ denoting the amplitude and phase difference, respectively, one can obtain the ratio between η_1 and η_2 . Here, A and φ can be manipulated by varying the geometric parameters of the SSR. Compared to the dipole response of the commonly used rectangular aperture,^[19–21] the SSR has a much higher design degree of freedom that is more suitable for the design of coupling-mediated devices. However, the complex structure of the SSR leads

to a lower efficiency. Section S1 in the Supporting Information makes a comparison between SSR- and rectangular aperture-constructed vortex generators, in which the conversion efficiency of the SSR-based device is shown to be about 1/3.7 of that of the rectangular aperture-based device.

The separation between the two SSRs in the radial direction, d , as shown in Figure 2b, is much smaller than the radius R , which causes S_{n-1} and S_{n-2} to comply with a paraxial approximation condition. Therefore, under the LCP and RCP incidences, the inward SP excitation $S_n^\pm \approx S_{n-1}^\pm + S_{n-2}^\pm$ from the n th SSR-pair can be described as^[20]

$$S_n^+ \propto [(\gamma_s + \gamma_a + \kappa)Ae^{i(\varphi - k_{\text{SP}}d)} + (\gamma_s + \gamma_a - \kappa)e^{-i\pi/2}]e^{i\theta_n} \quad (5a)$$

$$S_n^- \propto [(\gamma_s + \gamma_a - \kappa)Ae^{i(\varphi - k_{\text{SP}}d)} + (\gamma_s + \gamma_a + \kappa)e^{i\pi/2}]e^{-i\theta_n} \quad (5b)$$

where $k_{\text{SP}} = 2\pi/\lambda_{\text{SP}}$ is the SP wave number. Obviously, the items in the brackets are the same for all the n SSR-pairs, and hence the phase of the excited SPs by the n th SSR-pair only depends on the orientation angle θ_n , which means that the incident optical SAM $|\sigma\rangle$ is converted to plasmonic OAM $|e^{i\sigma\theta}\rangle$ with the same helicity. The conversion is robust and results from the geometric phase due to the rotation of SSR-pairs. By carefully designing the SSR-pair, the phase of the first term in the brackets $\varphi - k_{\text{SP}}d$ can be tuned to around $-\pi/2$, which results in a constructive excitation under the LCP incidence while a destructive excitation under the RCP incidence. Here the extinction of S^- is determined by the relative amplitudes of $(\gamma_s + \gamma_a - \kappa)A$ and $(\gamma_s + \gamma_a + \kappa)$, where γ_s , γ_a , and A mainly depend on the geometric parameters of the SSR, while κ is controlled by the distance s , providing the design degrees of freedom for a sufficient extinction.

Based on the above analysis, a realistic SSR-pair was appropriately selected by simulation. With the overall performance taken into consideration, the simulated SP intensity $|E_z|^2$ distributions of the eventually designed metasurface under the LCP and RCP incidences are shown in Figure 3a,d, respectively. The SPs excited by the LCP incidence successfully form a “doughnut” intensity profile in the center while the SPs excited by the RCP incidence are nearly negligible. Furthermore, the fitted results shown in Figure 3b,e agree well with the corresponding simulations, which confirms the theoretical analysis of selective conversion from optical SAM to plasmonic OAM. Figure 3c,f illustrates the corresponding simulated SP field (real part of E_z) distributions, where the phase evolution along the “doughnut” intensity profile equals 2π , corresponding to a charge 1 plasmonic vortex. In addition, a supplementary dynamic graphic is provided to show that the helicity of the converted plasmonic OAM is the same as the incident SAM. Notably, the generation of plasmonic vortices with a helicity opposite to that of the incident spin can be achieved by simply introducing a dynamic phase^[21,22] (see Sections S2 and S3 in the Supporting Information). For a clear comparison, Figure 4 illustrates the simulated and theoretically fitted SP intensity distributions along $y = 0$ mm for both LCP and RCP incidences. The full width at half maximum is less than $\lambda_{\text{SP}}/3$, providing a subwavelength scale on-chip force trap. Furthermore, a quantitative comparison of the selective conversion can be calculated

Figure 3. Simulated and theoretically fitted results. a,d) Simulated SP intensity ($|E_z|^2$) distributions at 0.75 THz of the metasurface excited by the LCP and RCP incidences, respectively. b,e) Theoretically fitted results of a $9 \times 9 \text{ mm}^2$ range corresponding to the blue dashed boxes marked in (a) and (d), respectively, where the fitting parameters are $\gamma_s = 0.201 \text{ rad ps}^{-1}$, $\gamma_a = 0.006 \text{ rad ps}^{-1}$, $\kappa = 0.075 \text{ rad ps}^{-1}$, $A = 2.51$, and $\varphi = -1.2 \text{ rad}$. c,f) Simulated SP field (real part of E_z) distributions at 0.75 THz of the metasurface excited by the LCP and RCP incidences, respectively. The inset arrow in the bottom-left corner of each picture represents the corresponding incident polarization state.

as the ratio of the peak intensities (see the marks in Figure 4), which is $I_{\text{LCP}}/I_{\text{RCP}} \approx 36.8$.

To experimentally verify the proposed design, a scanning near-field terahertz microscopy system,^[40] developed based on

Figure 4. SP intensity ($|E_z|^2$) distributions along $y = 0 \text{ mm}$ from the simulated and theoretically fitted results illustrated in Figure 3.

traditional terahertz time-domain spectroscopy, is applied to characterize the fabricated metasurface. A LT-GaAs-based near-field photoconductive antenna microprobe with a pair of electrodes sensitive to the E_z component is employed to directly measure the SP fields. To achieve a movable probe, the detection beam of the system is coupled into a 2 m length optical fiber. A predispersion compensation grating pair is employed to suppress the pulse stretching effect in the fiber. The probe is then fixed onto a 2D electrically controlled translation stage to enable the scanning function.^[40] The incident terahertz beam is collimated to a spot size of 5 mm diameter, which is large enough to cover the whole excitation range. The circular polarization state of the incident beam is controlled by the combination of a wire grid and a quarter-wave plate. During characterization, the detection probe is placed $\approx 50 \mu\text{m}$ above the metasurfaces, the same as in the numerical simulations. **Figure 5a,b** illustrates the measured SP intensity distributions under the LCP and RCP incidences, respectively, where selective conversion from optical SAM to plasmonic OAM can be clearly observed. Furthermore, **Figure 5c,d** illustrates the measured SP field distributions under the LCP and RCP incidences, respectively, where the 2π phase evolution can be observed. Despite slight differences between the measurement shown in **Figure 5a** and the simulation shown in **Figure 3a**, the measured LCP and RCP excitations, as shown in **Figure 5e**, experimentally confirm the proposed spin-coded selective conversion.

In conclusion, coupling-mediated selective conversion from optical SAM to plasmonic OAM by an SSR-pair-composed metasurface is theoretically proposed and experimentally demonstrated. Although only a plasmonic vortex with topological

Figure 5. Experimental results. a,b) Measured SP intensity ($|E_z|^2$) distributions at 0.75 THz in the case of the LCP and RCP incidences, respectively. c,d) Measured SP field (real part of E_z) distributions at 0.75 THz in the case of LCP and RCP incidences, respectively. e) SP intensity ($|E_z|^2$) distributions along $x = 0$ mm and $y = 0$ mm from the experimental results illustrated in (a) and (b), respectively. The inset microscopic image exhibits the LT-GaAs-based near-field microprobe, which was placed about 50 μm above the metasurface, with an inverted image from the reflection of the metasurface.

charge 1 was discussed here, by simply introducing a dynamic phase^[21,22] the proposed design scheme could be applied to vortex plasmons of arbitrary charges. As examples, Sections S2 and S3 in the Supporting Information present the design schematics and corresponding simulations of plasmonic vortex generators for different topological charges using the proposed SSR-pair. The spin-coded response in conjunction with dynamic polarization modulation techniques may open a gateway toward electrically reconfigurable applications including trapping and manipulating particles, on-chip quantum information processing and communications.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

coupled-mode theory, metasurfaces, spin-to-orbital angular momentum conversion, surface plasmons

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Supporting Information

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- [1] J. H. Poynting, *Proc. R. Soc. A* **1909**, 82, 546.
- [2] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, J. P. Woerdman, *Phys. Rev. A* **1992**, 45, 8185.
- [3] D. L. Andrews, M. Babiker, *The Angular Momentum of Light*, Cambridge University Press, Cambridge **2012**.
- [4] A. Nicolas, L. Veissier, L. Giner, E. Giacobino, D. Maxein, J. Laurat, *Nat. Photonics* **2014**, 8, 234.
- [5] D.-S. Ding, Z.-Y. Zhou, B.-S. Shi, G.-C. Guo, *Nat. Commun.* **2013**, 4, 2527.
- [6] M. Padgett, R. Bowman, *Nat. Photonics* **2011**, 5, 343.
- [7] G. Vallone, V. D'Ambrosio, A. Sponselli, S. Slussarenko, L. Marrucci, F. Sciarrino, P. Villoresi, *Phys. Rev. Lett.* **2014**, 113, 060503.
- [8] N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A. E. Willner, S. Ramachandran, *Science* **2013**, 340, 1545.
- [9] Y. Chen, J. Gao, Z.-Q. Jiao, K. Sun, W.-G. Shen, L.-F. Qiao, H. Tang, X.-F. Lin, X.-M. Jin, *Phys. Rev. Lett.* **2018**, 121, 233602.

- [10] G. Biener, A. Niv, V. Kleiner, E. Hasman, *Opt. Lett.* **2002**, 27, 1875.
- [11] L. Marrucci, C. Manzo, D. Paparo, *Phys. Rev. Lett.* **2006**, 96, 163905.
- [12] R. C. Devlin, A. Ambrosio, N. A. Rubin, J. P. B. Mueller, F. Capasso, *Science* **2017**, 358, 896.
- [13] Y. Zhang, W. Liu, J. Gao, X. Yang, *Adv. Opt. Mater.* **2018**, 6, 1701228.
- [14] Y. Zhang, J. Gao, X. Yang, *Adv. Opt. Mater.* **2019**, 7, 1801486.
- [15] K. Y. Bliokh, F. J. Rodríguez-Fortuño, F. Nori, A. V. Zayats, *Nat. Photonics* **2015**, 9, 796.
- [16] Y. Gorodetski, A. Niv, V. Kleiner, E. Hasman, *Phys. Rev. Lett.* **2008**, 101, 043903.
- [17] W. Chen, D. C. Abeysinghe, R. L. Nelson, Q. Zhan, *Nano Lett.* **2010**, 10, 2075.
- [18] H. Kim, J. Park, S.-W. Cho, S.-Y. Lee, M. Kang, B. Lee, *Nano Lett.* **2010**, 10, 529.
- [19] N. Shitrit, I. Bretner, Y. Gorodetski, V. Kleiner, E. Hasman, *Nano Lett.* **2011**, 11, 2038.
- [20] J. Lin, J. P. B. Mueller, Q. Wang, G. Yuan, N. Antoniou, X.-C. Yuan, F. Capasso, *Science* **2013**, 340, 331.
- [21] Q. Tan, Q. Guo, H. Liu, X. Huang, S. Zhang, *Nanoscale* **2017**, 9, 4944.
- [22] G. Spektor, D. Kilbane, A. K. Mahro, B. Frank, S. Ristok, L. Gal, P. Kahl, S. Mathias, H. Giessen, F.-J. Meyer zu Heringdorf, M. Orenstein, M. Aeschlimann, *Science* **2017**, 355, 1187.
- [23] W.-Y. Tsai, J.-S. Huang, C.-B. Huang, *Nano Lett.* **2014**, 14, 547.
- [24] X. Yin, Z. Ye, J. Rho, Y. Wang, X. Zhang, *Science* **2013**, 339, 1405.
- [25] K. Y. Bliokh, D. Smirnova, F. Nori, *Science* **2015**, 348, 1448.
- [26] E. Plum, V. A. Fedotov, A. S. Schwanecke, N. I. Zheludev, *Appl. Phys. Lett.* **2007**, 90, 223113.
- [27] A. Kavokin, G. Malpuech, M. Glazov, *Phys. Rev. Lett.* **2005**, 95, 136601.
- [28] C. Leyder, M. Romanelli, J. Ph. Karr, E. Giacobino, T. C. H. Liew, M. M. Glazov, A. V. Kavokin, G. Malpuech, A. Bramati, *Nat. Phys.* **2007**, 3, 628.
- [29] M. Onoda, S. Murakami, N. Nagaosa, *Phys. Rev. Lett.* **2004**, 93, 083901.
- [30] X. Ling, X. Zhou, K. Huang, Y. Liu, C.-W. Qiu, H. Luo, S. Wen, *Rep. Prog. Phys.* **2017**, 80, 066401.
- [31] E. Plum, V. A. Fedotov, N. I. Zheludev, *Appl. Phys. Lett.* **2008**, 93, 191911.
- [32] Z. J. Wang, H. Jia, K. Yao, W. S. Cai, H. S. Chen, Y. M. Liu, *ACS Photonics* **2016**, 3, 2096.
- [33] W. Ma, F. Cheng, Y. M. Liu, *ACS Nano* **2018**, 12, 6326.
- [34] X. Zhang, Q. Xu, Q. Li, Y. Xu, J. Gu, Z. Tian, C. Ouyang, Y. Liu, S. Zhang, X. Zhang, J. Han, W. Zhang, *Sci. Adv.* **2016**, 2, e1501142.
- [35] T. Zentgraf, T. P. Meyrath, A. Seidel, S. Kaiser, H. Giessen, C. Rockstuhl, F. Lederer, *Phys. Rev. B* **2007**, 76, 033407.
- [36] A. Bitzer, A. Ortner, H. Merbold, T. Feurer, M. Walther, *Opt. Express* **2011**, 19, 2537.
- [37] S. Fan, W. Suh, J. D. Joannopoulos, *J. Opt. Soc. Am. A* **2003**, 20, 569.
- [38] W. Suh, Z. Wang, S. H. Fan, *IEEE J. Quantum Electron.* **2004**, 40, 1511.
- [39] S. Assaworrorarit, X. Yu, S. Fan, *Nature* **2017**, 546, 387.
- [40] Y. Xu, X. Zhang, Z. Tian, J. Gu, C. Ouyang, Y. Li, J. Han, W. Zhang, *Appl. Phys. Lett.* **2015**, 107, 021105.