Current Applied Physics 45 (2023) 72–75

Contents lists available at ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

Topological surface plasmon resonance in deep subwavelength structure

Yu Sung Choi [1], Ki Young Lee [1], Jae Woong Yoon *

Department of Physics, Hanyang University, Seoul, 04763, South Korea

ARTICLE INFO

Keywords:
Topological effect
Guided-mode resonance
Plasmonic
Subwavelength grating

ABSTRACT

We propose a plasmonic topological junction structure that combines topological robustness and subwavelength localization properties. The proposed structure is a junction of two topologically distinguished metal-insulator-metal waveguide gratings. Assuming Au–SiO_2–Au waveguide gratings, we theoretically demonstrate a plasmonic Jackiw-Rebbi-state resonance which has substantially small effective mode-field area in the order of 0.1 μm^2 at 1560 nm wavelength and requires only 10 periods for fully sustaining the ideal resonance Q-factor of the infinitely large array. Therefore, our proposed approach provides an efficient scheme for creating various plasmonic leaky-mode resonance components that can take advantages of spectral robustness and strong localization properties.

1. Introduction

Topological effects in the condensed matter physics [1–3] have been applied to photonic structures [4] as a novel approach to obtain strong optical localization and robust functionalities against inevitable fabrication imperfections. Introduction of topological phase transition effects to photonic nanostructures have successfully created active guided-light steering method [5], topological edge-state resonators [6], high-power single-mode lasers [7,8], to mention just a few.

One of the most fundamental topological states is a Jackiw-Rebbi state, a state localized at a junction of two topologically distinguished 1D lattices [9,10], showing robust resonance features against random structural errors [11]. A Jackiw-Rebbi state produces a strong localization effect in the absence of any explicit cavity structure and the localization profile is readily tunable with effective Dirac-mass control in the lattice structure. Therefore, Jackiw-Rebbi states can be efficiently used for various wave-control devices including resonators [11], beam emitters [12], and optical funnels [13].

In particular, leaky-mode resonances based on photonic Jackiw-Rebbi states is of interest because it provides the topological protection and remarkable reduction of device footprint size while potentially maintaining versatile functionalities of leaky-mode-resonance thin-film devices as spectral filters, sensor templates, absorbers, reflectors, polarizers, and wave plates [11,15]. In this consideration, it is highly desirable to further reduce footprint size by combining additional localization mechanism since there is constant demand for higher integration capability and stronger light-matter interaction in such devices. Toward this end, plasmonic topological states have been theoretically suggested in some structures including 1D plasmonic crystals in a metal-insulator-metal waveguide [16], plasmonic channel waveguides [17], and graphene-coupled plasmonic Su-Schrieffer-Heeger chains [18]. Although they theoretically demonstrate the topological states localized at the junctions, these approaches are primarily based on the first-order Bragg condition and thereby the leakage radiation that mediates the leaky-mode resonance from the out-of-plane light incidence is not allowed.

In this paper, we propose a plasmonic Jackiw-Rebbi-state resonance thin-film structure that takes advantages of topological and enhanced localization properties in the second-order Bragg condition regime. We study a topological junction of metal-insulator-metal (MIM) zero-order gratings. In this structure, parametric control of the coupling constant between two counter-propagating deep-subwavelength plasmonic modes leads to the topological phase transition of the associated leaky-mode resonance states. We provide an experimentally presumable design based on Au–SiO_2 interfaces for resonant excitations in the optical telecommunications band. We obtain effective mode area $A_{eff} \approx 8 \times 10^{-2}$ μm^2, which is 135 times smaller than a compatible pure photonic Jackiw-Rebbi-state resonance. In addition, we numerically demonstrate almost constant resonance quality (Q) factor for remarkably small footprint size down to 10 periods. Our results could give practical potential for developing a high efficiency optical phased array based on topological physics, which avoid unintended losses as much as possible.

---

* Corresponding author.
E-mail address: yoonjw@hanyang.ac.kr (J.W. Yoon).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.cap.2022.11.002
Received 30 June 2022; Received in revised form 12 October 2022; Accepted 4 November 2022

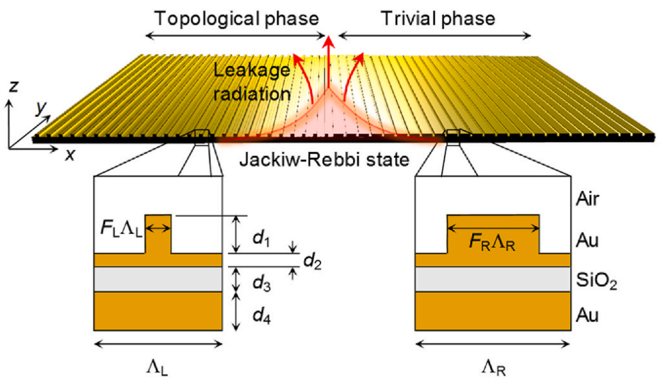

Fig. 1. Schematic diagram of a Metal-Insulator-Metal device with a metallic lattice capable of excitation of the topological interface state. The left side of the enlarged view is a unit cell with $F = 0.3$ and has a topological phase. On the other hand, the right side is a unit cell with $F = 0.8$ and has a trivial phase.

2. Topological phase transition

We consider an MIM zero-order grating structure based on Au–SiO$_2$ interfaces as schematically illustrated in Fig. 1. The structure consists of a junction of two grating structures with identical layer thickness configuration but different fill factors F_L and F_R in order to have the two gratings in distinguished topological phases for surface-plasmonic mode primarily infiltrated in the insulator (SiO$_2$) layer. Periods Λ_L and Λ_R are also different from each other so that the two gratings share an identical bandgap center for the second-order Bragg condition.

Under a certain appropriate choice of a parameter set, the junction supports a plasmonic Jackiw-Rebbi state in the in the similar manner as the photonic counterpart [11,14]. We note in Ref. [14] that the difference between transverse electric (TE) and transverse magnetic (TM) leaky modes in the topological band dynamics exist due to the TM surface effect in addition to the Bragg-diffraction effect in both polarization, leading to the difference in the critical parameter values, but the essential underlying physics of the topological phase transition is identical with respect to the effective momentum-space Hamiltonian. The topological phase transition in leaky-mode resonance structures occurs at a certain critical condition where the diffractive coupling between two counter-propagating guided modes vanishes as a result of destructive interference between the first-order and second-order diffraction pathways [14,19,20]. Since relative magnitudes and phases of the first and second order diffraction pathways are primarily determined by fill factor F of a grating structure, F is thereby a key factor that controls the topological phase. This also applies to the surface-plasmonic grating structure that we treat here.

We optimize the structure parameters such that the second-order bandgap is centered at 1560 nm and as wide as possible. The reason for a preferably wide bandgap is that lateral footprint size of a Jackiw-Rebbi state is inversely proportional to spectral width of the bandgap and we are perusing a state as small as possible here. A trial optimization yields $d_1 = 100$ nm, $d_2 = 10$ nm, $d_3 = 10$ nm, $d_4 = 200$ nm, $\Lambda = 370$–420 nm, and critical fill factor $F_c = 0.6$ for the critical topological phase. The

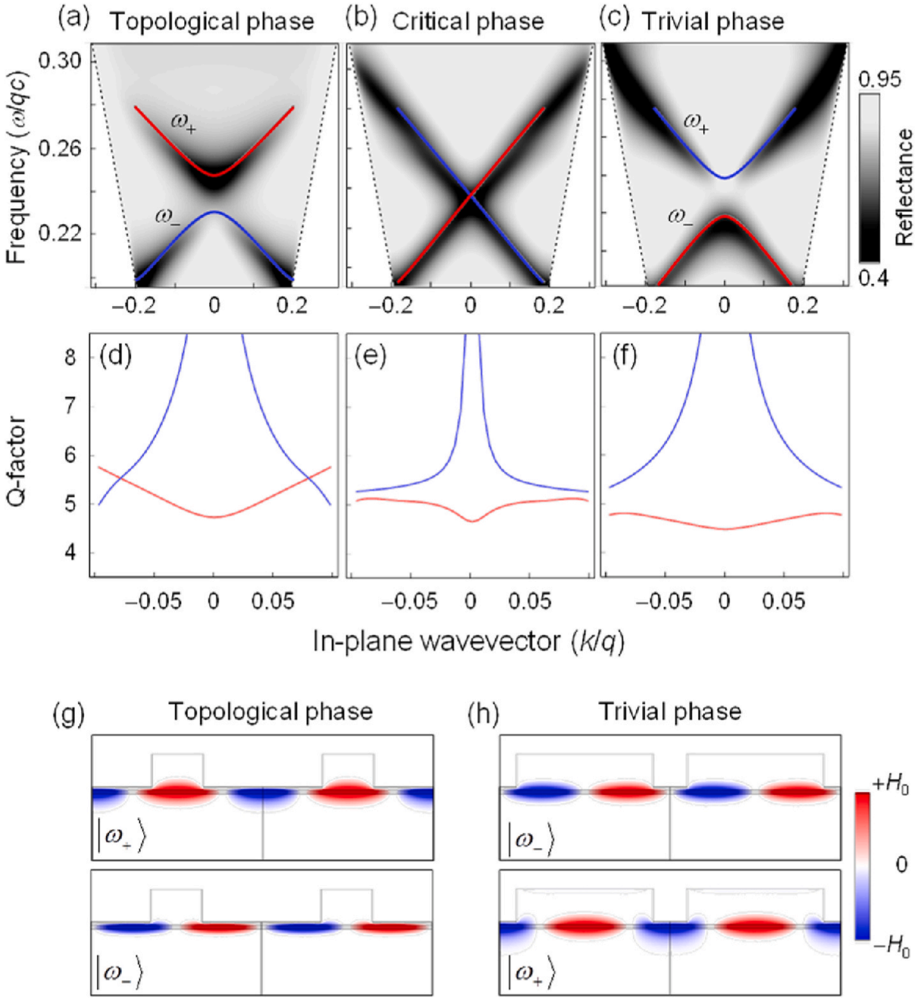

Fig. 2. Topological band transition by structural parameter change. (a) ~ (c) represent the reflection spectrum and dispersion relation at $F = 0.3$, 0.6, 0.8, respectively. (d) ~ (f) indicate the Q-factor for the structure having each fill-factor. The red and blue lines represent symmetric states and anti-symmetric states, respectively. (g) ~ (h) are the field distribution at the gamma point. q represents grating momentum, $q = 2\pi/\Lambda$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

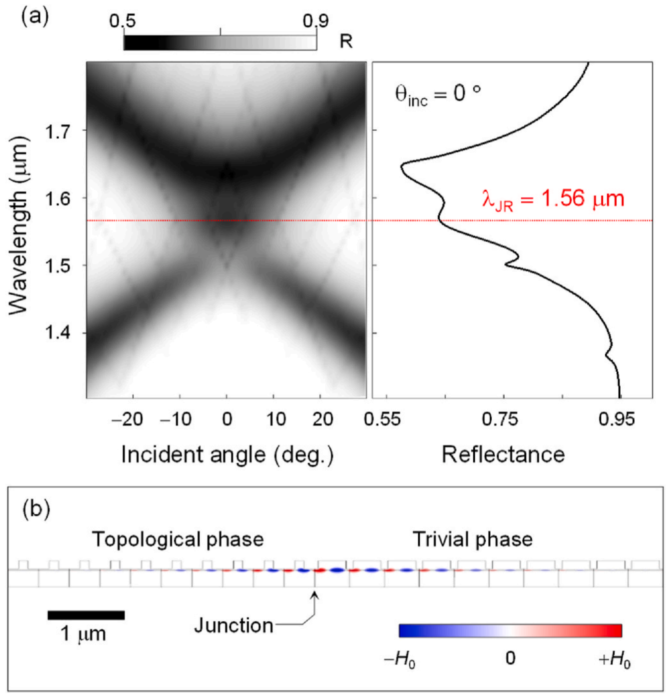

Fig. 3. Jackiw-Rebbi state at a plasmonic topological interface. (a) Reflection spectra for incident angle and the right indicates only for the normal incident light. Red dashed-line represents wavelength at which the Jackiw-Rebbi is excited. (b) represents H-field distribution of the Jackiw-Rebbi state in the plasmonic topological junction structure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

topological phase transition at F_c for this structure is confirmed in the resonance spectrum and associated field patterns as shown in Fig. 2. We provide the detailed description for the roles of structural parameters to generate topological phase transitions in Supplementary Materials [21].

In Fig. 2(a) ~ 2(c), we show F-dependent reflectance spectrum on the frequency-wavevector plane for the second-order bandgap. We use the rigorous couple-wave analysis [22] for this calculation. For $F = 0.3 < F_c$ in Fig. 2(a), the upper (ω_+) and lower (ω_-) bands appear as resonance dips. At their band edges ($k = 0$), ω_+ state manifests as a super-radiant resonance with an enhanced linewidth while ω_- state leads to a sub-radiant resonance with a vanishingly narrow linewidth by the excitation of a symmetry-protected bound state in the continuum (BIC). For $F = F_c = 0.6$ in Fig. 2(b), the bandgap closes as results of the zero coupling between the counter-propagating modes where the super and sub-radiant states are degenerated at $k = 0$. For $F = 0.8 > F_c$ in Fig. 2(c), the bandgap opens again and the super/sub-radiant resonance features reappear but their locations flip with respect to the spectrum for $F = 0.3 < F_c$ in Fig. 2(a). This is a characteristic property involved in the topological phase transition that accompanies an exchange of modal symmetry between the upper and lower band eigenstates [23] as confirmed in the corresponding field patterns in Fig. 2(g) and (h).

We show the Q-factor spectra for $\omega_\pm$ bands in Fig. 2(d) ~2(f). The infinite Q-factor at $k = 0$ for all three cases clearly indicates the conservation of a topological charge carried by the symmetry-protected BIC [24]. We use the finite element method for all these calculations [25].

In further detail, the case for $F = 0.3 < F_c$ corresponds to the topological phase where ω_+ and ω_- bands take π for their Zak phases, *i.e.*, 1 for the winding number, and the other case for $F = 0.8 > F_c$ corresponds to the trivial phase with 0 Zak phases for the upper and lower bands.

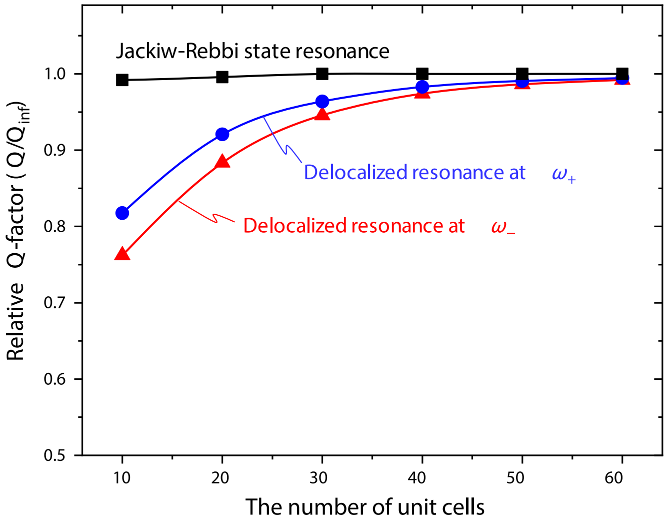

Fig. 4. Q-factor for the number of a unit cell (N). Q_{inf} is the Q-factor when the number of the unit cell is infinite. The black line represents the Q-factor of the Jackiw-Rebbi state, and the red and blue line indicate the Q-factor of the conventional gap plasmon in the case of $F = 0.3$, $F = 0.8$, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Plasmonic topological interface state

We now consider a junction of these two surface-plasmonic gratings in order to see if it supports a desired Jackiw-Rebbi state as a topological interface state with an extremely strong optical confinement property in both lateral and vertical axes. We show the angle-dependent reflectance spectrum of a junction in Fig. 3(a). We identify a plasmonic Jackiw-Rebbi resonance feature at 1560 nm in the middle of the bandgap between 1500 nm and 1640 nm in analogy to the zero-energy state of the Dirac equation.

We show associated field distribution in Fig. 3(b). It shows desired strong localization with vertical and lateral confinement lengths ~20 nm and 4 μm, when estimated by taking an intensity-weighted average length value. For confirm the dependence of the Jackiw-Rebbi state on the thickness of the metal film, we also perform the same calculation as above for the case of $d_2 = 20$ nm in Supplementary Material. Corresponding effective mode area is 8×10^{-2} μm^2, which is 135 times smaller than the compatible pure photonic Jackiw-Rebbi state resonance. The pure photonic Jackiw-Rebbi-resonance structure in this comparison consists of a junction of two fully-etched SiO$_2$ grating with 1.5 μm thickness composed with a dielectric material identical to the MIM structure, $\Lambda_L = 1.47$ μm, $F_L = 0.2$, $\Lambda_R = 1.18$ μm, and $F_R = 0.8$. These parameters are chosen such that the structure supports a fundamental transvers-electric-guided mode with the smallest vertical confinement length.

Resonance Q-factor is in general a key parameter for spectral selectivity of intensity or phase distributions and cavity quantum-electrodynamic coupling effects. For leaky mode resonances in periodic thin-film structures, reduction of lateral footprint size under a certain critical scale essentially evolves degradation of Q-factor because of energy loss towards the truncation edges. Use of the proposed plasmonic Jackiw-Rebbi resonance may have a great advantage in this consideration.

4. Resonance Q-factor

In Fig. 4, we show the lateral-size-dependent Q-factor for the plasmonic Jackiw-Rebbi resonance in comparison with the delocalized resonances at the upper (ω_+) and lower (ω_-) band edges. For delocalized band-edge resonances, associated Q-factor curves substantially decreases as the number N of periods within the device area decreases under 30 periods, approaching down around 80% of their infinitely-large array cases (Q_{inf}) for $N = 10$. In contrast, the Q-factor for the Jackiw-Rebbi resonance is almost constant in the entire N domain from 10 to 60. In particular, substantial degradation in Q-factor under 90% of Q_{inf} is found for $N < 8$ corresponding to lateral footprint size <3.2 μm, which is comparable to the smallest pixel size in the present state-of-the-art CMOS image sensors. This property is favorable for high-density integration of leaky-mode-resonance devices in addition to the topological robustness against structural imperfections.

5. Conclusion

In conclusion, we have proposed a MIM waveguide-grating junction structure that produces a plasmonic topological resonance effect with mode-field area being two-order-of-magnitude smaller than the pure photonic counterpart. We have demonstrated plasmonic topological phase transition of a periodically modulated MIM waveguide at the second-order Bragg condition with grating fill-factor control. A junction of two Au–SiO_2–Au waveguide gratings with different fill factors supports a plasmonic Jackiw-Rebbi-state resonance that requires only 10 periods for sustaining the ideal resonance Q-factor of the infinitely large array. It corresponds to only two vacuum wavelengths. Therefore, the plasmonic topological junction provides an efficient method to create robust resonance excitation in a highly compact spatial region. By considering these characteristic features of plasmonic topological resonances, further study on implementation of optical phased-array element and its tunable operation is of practical importance for all-solid state LiDAR [26] and spatial light modulators [27].

Data availability

The data that support the findings of this study are available from the corresponding author up on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the Leader Researcher Program (NRF-2019R1A3B2068083), the Basic Science Research Program (NRF-2018R1A2B3002539), NRF Sejong Science fellowship (NRF-2022R1C1C2006290), and the research fund of Hanyang University (HY-202000000000513).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cap.2022.11.002.

References

[1] X.-L. Qi, S.-C. Zhang, Topological insulators and superconductors, Rev. Mod. Phys. 83 (2011) 1057.
[2] H. Shen, B. Zhen, L. Fu, Topological band theory for non-hermitian Hamiltonians, Phys. Rev. Lett. 120 (2018), 146402.
[3] J.M. Zeuner, M.C. Rechtsman, Y. Plotnik, Y. Lumer, S. Nolte, M.S. Rudner, M. Segev, A. Szameit, Observation of a topological transition in the bulk of a non-hermitian system, Phys. Rev. Lett. 155 (2015), 040402.
[4] A. Tomita, R.Y. Chiao, Observation of berry's topological phase by use of an optical fiber, Phys. Rev. Lett. 57 (1986) 937.
[5] H. Zhao, X. Qiao, T. Wu, B. Midya, S. Longhi, L. Feng, Non-Hermitian topological light steering, Science 365 (6458) (2019) 1163–1166.
[6] G.Q. Liang, Y.D. Chong, Optical resonator analog of a two-dimensional topological insulator, Phys. Rev. Lett. 110 (2013), 203904.
[7] Y. Ota, R. Katsumi, K. Watanabe, S. Iwamoto, Y. Arakawa, Topological photonic crystal nanocavity laser, Commun. Phys. 1 (2018) 86.
[8] Y. Gong, S. Wong, A.J. Bennett, D.L. Huffaker, S.S. Oh, Topological insulator laser using valley-Hall photonic crystals, ACS Photonics 7 (2020) 2089.
[9] F.F. Li, H.X. Wang, Z. Xiong, Q. Lou, P. Chen, R.-X. Wu, Y. Poo, J.H. Jiang, S. John, Topological light-trapping on a dislocation, Nat. Commun. 9 (2018) 2462.
[10] T.X. Tran, H.M. Nguyen, D.C. Duong, Jackiw-Rebbi states in interfaced binary waveguide arrays with Kerr nonlinearity, Phys. Rev. 100 (2019), 053849.
[11] K.Y. Lee, K.W. Yoo, Y. Choi, G. Kim, S. Cheon, J.W. Yoon, S.H. Song, Topological guided-mode resonances at non-Hermitian nanophotonic interfaces, Nanophotonics 10 (7) (2021) 1853–1860.
[12] A. Foehr, O.R. Bilal, S.D. Huber, C. Daraio, Spiral-based phononic plates: from wave beaming to topological insulators, Phys. Rev. Lett. 120 (2018), 205501.
[13] S. Weidemann, M. Kremer, T. Helbig, T. Hofmann, A. Stegmaier, M. Greiter, R. Thomale, A. Szameit, Topological funneling of light, Science 368 (6488) (2020) 311–314.
[14] S.G. Lee, S.H. Kim, C.S. Kee, R. Magnusson, Polarization-differentiated band dynamics of resonant leaky modes at the lattice Γ point, Opt Express 28 (26) (2020) 39453–39462.
[15] G. Quaranta, G. Basset, O.J.F. Martin, B. Gallinet, Recent advances in resonant waveguide gratings, Laser Photon. Rev. 12 (9) (2018), 1800017.
[16] L. Wabg, W. Cai, M. Bie, X. Zhang, J. Xu, Zak phase and topological plasmonic Tamm states in one-dimensional plasmonic crystals, Opt Express 26 (22) (2018) 28963–28975.
[17] Q. Cheng, Y. Pan, Q. Wang, T. Li, S. Zhu, Topologically protected interface mode in plasmonic waveguide arrays, Laser Photon. Rev. 9 (4) (2015) 392–398.
[18] T.G. Rappoport, Y.V. Bludov, F.H.L. Koppens, N.M.R. Peres, Topological graphene plasmons in a plasmonic realization of the su–schrieffer–heeger model, ACS Photonics 8 (6) (2021) 1817–1823.
[19] S.G. Lee, R. Magnusson, Band flips and bound-state transitions in leaky-mode photonic lattices, Phys. Rev. B 99 (2019), 045304.
[20] S.G. Lee, R. Magnusson, Band dynamics of leaky-mode photonic lattices, Opt Express 27 (13) (2019) 18180–18189.
[21] P. Berini, Long-range surface plasmon polaritons, Adv. Opt Photon 1 (2009) 484–588.
[22] M.G. Moharam, T.K. Gaylord, Rigorous coupled-wave analysis of planar-grating diffraction, JOSA 71 (7) (1981) 811–818.
[23] L. Lu, J.D. Joannopoulos, M. Soljacic, Topological photonics, Nat. Photonics 8 (11) (2014) 821–829.
[24] B. Zhen, C.W. Hsu, L. Lu, A.D. Stone, M. Soljačić, Topological nature of optical bound states in the continuum, Phys. Rev. Lett. 113 (2014), 257401.
[25] W.B.J. Zimmerman, Multiphysics Modelling with Finite Element Methods, vol. 18, World Scientific Publishing Company, 2006.
[26] J. Park, B.G. Jeong, S.I. Kim, D. Lee, J. Kim, C. Shin, C.B. Lee, T. Otsuka, J. Kyoung, S. Kim, K. Yang, Y. Park, J. Lee, I. Hwang, J. Jang, S.H. Song, M.L. Brongersma, K. Ha, S. Hwang, H. Choo, B.L. Choi, All-soild-state spatial light modulator with independent phase and amplitude control for three-dimensional LiDAR applications, Nat. Nanotechnol. 16 (2021) 69–76.
[27] K. Du, H. Barkaoui, X. Zhang, L. Jin, Q. Song, S. Xiao, Optical metasurfaces towards multifunctionality and tunability, Nanophotonics 11 (2022) 1761–1781.