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Wavelength-Scale Photonic Space Switch Proof-Of-Concept Based on Photonic Hook Effect

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Abstract
The proof-of-concept of a new wavelength-scaled all-optical two-channel switch based on the photonic hook phenomenon is proposed and demonstrated. By means of the numerical finite-difference time-domain simulations, several prototypes of such devices are considered based on dielectric microstructures with broken symmetry of both geometric shape and optical properties without the use of micromechanical devices or non-linear materials. Due to the unique property of the photonic hook to change its curvature depending on the optical wavelength, the proposed switch is a promising candidate for the implementation of optical switching in modern optoelectronics and miniature "on-chip" devices. Optical isolation that is close to 20 dB is discovered at the wavelengths of 1.5 and 1.9 µm for a dielectric Janus microbar-based switch with linear dimensions of about $(6\lambda)^3$ (λ is the wavelength of the incident plane wave).

1. Introduction
In the modern era of big data, a major challenge lies in realizing the abilities to transfer, switching, and process a large amount of various data. Optical switching technology and related optical switches devices are key elements in the applications of advanced network communications.[1] The significant growth in data generations and the rapid development of Dense Wavelength Division Multiplexing (DWDM) technology demand more reliable and flexible signal transfer and processing tools. In particular, the ability to optimize, route, and communicate data by optical methods is becoming crucial. In addition, modern requirements for microminiaturization of devices dictate the need for the development of optical components and "on-chip" devices, since fast real-time reconfiguration using integrated optical circuit technologies will provide energy efficiency and transparent data transmission and switching at high speed (as opposed to switching circuits based on traditional electronic components requiring control of an external electrical signal).[2] Optical switches are widely used both in testing fiber-optic components and for "neuromorphic" optical computations mimicking the brain functions to parallelly process and store data and information.[3]

Various types of optical switches are developed up to date.[1, 4-8] Among them, for example, the wavelength selective switches have received a lot of attention due to the capability to independently route optical signals to the channels depending on the wavelengths.[9-12] An optical switch of this type is a typical combination of a grating spectrometer and a spatial light modulator.[1] In this paper, we propose a new concept of a wavelength selective all-optical switch based on a recently discovered curved spatially localized light beams referred to as a photonic hook, which is produced by asymmetric dielectric particles with the wavelength-scale dimensions illuminated by a light wave.[13, 14] This concept allows for a non-mechanical and all-optical on-chip switch that changes the direction of the output light beam without the use of non-linear materials.[15]

2. Photonic Hook-Based Optical Switching Concept
The principle of the proposed wavelength selective switch is illustrated in Figure 1a–d. The switch utilizes the effect of a photonic hook [13, 14] which is realized by the propagation of an optical wave through a specifically diffractive optical element (DOE) (dielectric microparticle), which imparts an asymmetric shift to the optical phase. After passing the dielectric microparticle, the optical wave acquires the wavefront curvature represented as an asymmetry of the transverse distribution of the

optical field. A part of the radiation tends to focus at a certain angle along with the light incidence in the form of a bent focus known as Minin's photonic hook phenomenon. [13, 14] The asymmetry of the wavefront can be achieved in several ways. Basically, the most common method is to use an optically homogeneous dielectric microparticle with an asymmetric geometrical shape (or an asymmetry of the illuminating beam). For example, this can be a rectangular prism, [13, 14, 16] a circular cylinder [17] or an ellipsoid under side illumination,[18] an asymmetric planar lens in the form of an off-axis Fresnel zone plate (FZP),[19] etc. Another way to obtain a curved photonic flux is to use the geometrically symmetric particles, but with a specially imposed asymmetry of the internal refractive indices. These are the so-called Janus particles, obtained by combining two or more materials with different optical properties.[20]

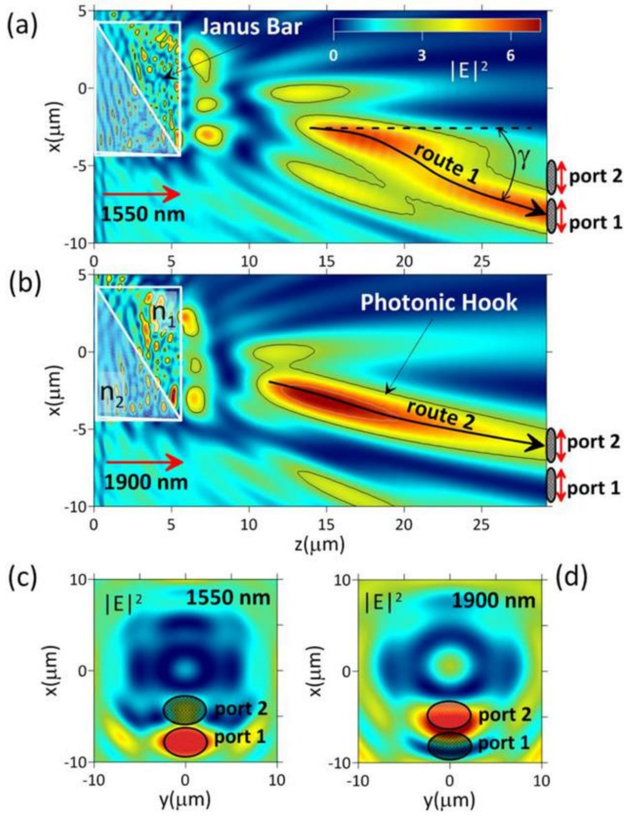

Figure 1 Optical switching based on a photonic hook. a,b) Longitudinal and c,d) transverse profiles of the optical intensity, $|E|^2$, near a Janus bar at the laser wavelengths providing switching between ports 1 and 2.

An important property of the photonic hook to realize, for example, the function of an optical switch, is the dependence of the angle of curvature of its arms on the illumination wavelength. Thus, with a certain spatial configuration of the photonic microstructure and receiver area, it becomes possible to achieve a change in the optical signal in each of the switching channels with a change in the radiation wavelength. Indeed, consider Figures 1a and 1b showing the two-dimension (2D) distribution of the squared amplitude (intensity), $|E|^2$, of a plane optical wave with the wavelengths of 1550 and 1900 nm, respectively, when scattered by a rectangular Janus bar composed of two optical materials with different refractive indices, n_1 = 1.5 and n_2 = 2. It is clear that the bending angle, γ, of the photonic hooks arising behind the particle is different. For the illumination with the wavelength of λ = 1550 nm, γ ≈ 21°, and at λ = 1900 nm, we observe γ ≈ 15°. If one places two optical receivers indicated in the figures as "port 1" and "port 2" in the z = 30 μm plane, this provides different field amplitude in each receiving channels, that is, their space switching by the optical signal amplitude. Obviously, the feasibility and reliability of the operation of such a switch are determined by the value of the optical isolation between the channels, which, in turn, depends on the parameters of the switching microparticle and the range of radiation wavelengths. In the next section of our work we search for the optimal designs of a dielectric diffractive element that provides the best switching of optical channels.

3. Optical Switch Optimization

Computer simulations of the proposed optical switches are carried out on the basis of the numerical solution of Maxwell equations for electromagnetic field vectors in three dimension (3D) spatio-temporal (3D+1) space using the finite-difference time-domain (FDTD) technique implemented in the Lumerical FDTD package (ver. 8.19). A photonic microstructure acting as a DOE, is placed within a 3D mesh-grid region, which is constructed in ambient air with the refractive index $n_0 = 1$ and is surrounded by a system of perfectly absorbing layers in order to implement the conditions of free radiation at the outer boundaries in the computational domain. A plane optical wave illuminating the plate, propagates in the direction of the wave vector k along the normal to the substrate with an optical switch placed on it and, for definiteness, has initial amplitude of 1 V m^{-1} and linear polarization along the x-axis. For the discretization of the computational domain, we employ the adaptive spatial grid with minimum and maximum steps of 0.5 and 50 nm, respectively, providing automatic crowding of the grid cells in the areas with the large dielectric constant gradients. The time step of the numerical advancing scheme is set to 0.25 fs in accordance with the Courant–Friedrichs–Lewy condition. In this case, the total number of Yee cells of the simulated domain amounts to about 14 millions.

Different types of asymmetric photonic structures used in the numerical simulations are shown in Figure 2a. They included two types of homogeneous rectangular glass prisms with a refractive index $n_1 = 1.5$, a rectangularly bifid Janus bar with different refractive indices of the halves, $n_1 = 1.5$, $n_2 = 2$, as well as an off-axis binary FZP with zones etched into a glass substrate with n1 = 1.5. Note that the switch prototypes with ordinary and flipped prisms shown in Figure 2a,b have not been previously considered in the literature for the production of a photonic hook. The geometrical dimensions of the prisms and Janus bar are chosen from the condition of obtaining the highest photonic hook curvature when illuminated by a light wave in the range from λ = 1200 to 2000 nm and are as follows (Figure 2b): L = 9 µm, h = 4.5 µm, d = L, t = 3.5 µm.

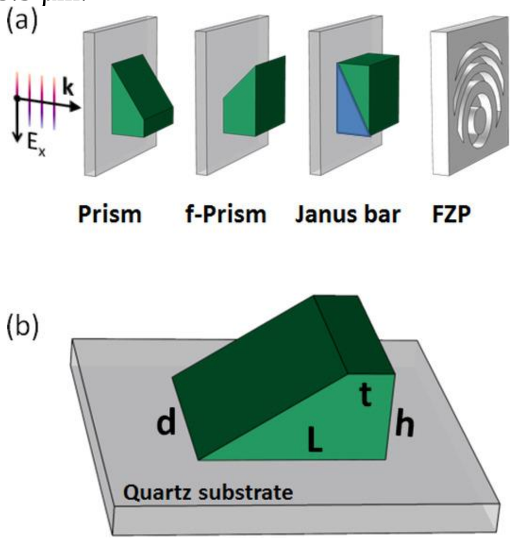

Figure 2 a) Different wavelength-scale DOEs used for photonic hook simulations: rectangular prism, flipped prism, Janus bar, off-axis Fresnel zone plate. b) Scheme of the prism-based optical switch on a substrate.

The binary zone plate consists of seven phase-alternating zones and is designed for the wavelength λ = 1550 µm and a focal length f = 15 µm at zone etching depth close to one wavelength, λ, providing the maximum optical intensity at the focus.[21] The spatial tilt of the near-field focus is provided by the use of a circular diaphragm with the aperture of 6 µm which is placed off-axis and thus opens the asymmetric configuration of the Fresnel zones for operation.

Worthwhile noting, for providing the optical space switching using the proposed concept, one should ensure good spatial isolation of the channels. This means that the proposed optical switcher, and the related photonic hook, should be long enough for providing sufficient spatial separation of the receiving ports. According to our simulations, this requirement is satisfied for the photonic hooks produced by rectangular particles, for example, prisms and bars, whereas the most intense photonic jet by a spherical particle has the shortest spatial length.

2D distributions of optical intensity near various DOEs are shown in Figure 3a–d. As seen, all the structures under study produce the localized curved photonic jets inclining toward the thicker part of the particles. For homogeneous prismatic particles, this corresponds to the optical flux inclination to their vertical facet, whereas for a two-component Janus particle the inclination of the photonic jet toward the half with a higher refractive index (n_2) is observed. The analysis of the presented intensity profiles shows that the largest bending angle of the photonic jet is realized for ordinary prism and inhomogeneous Janus bar, while FZP produces the best focusing of the incident optical wave, but the smallest bend, γ, of the photonic hook. The last parameter of γ is especially important because it determines the minimum distance at which it is possible to perform spatial separation of the optical channels having a given receiving aperture, and therefore γ directly affects the compactness of the proposed switches.

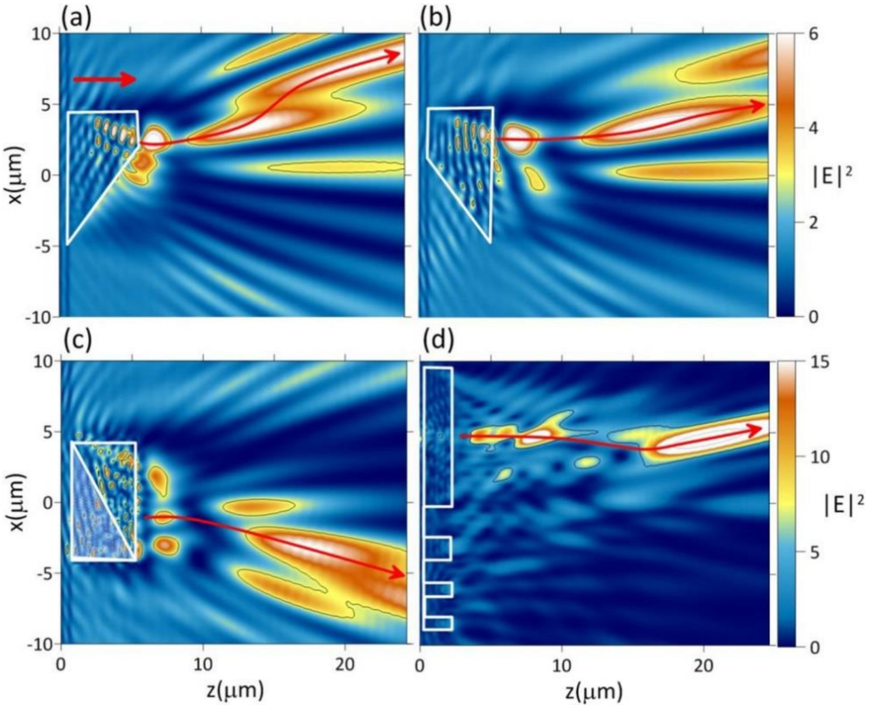

Figure 3 Simulated photonic hook formation by various wavelength-scales (DOEs with broken symmetry of optical properties. a–d) 2D distributions of optical intensity, $|E|^2$, produced by a plane wave (λ = 1550 µm) near prism (a), flipped prism (b), Janus bar (c), and off-axis FZP (d).

Referring to Figure 1c, we note that to improve the optical isolation of the switched channels it is necessary to set the input aperture area of the receiving ports according to the cross section of the photonic jet. In the case of meso-wavelength DOEs, the characteristic diameter of the photonic hook measured at the point of maximum intensity is on the order of the radiation wavelength.[22] It is found that the size of the photonic hook broadens during the propagation due to the diffraction. Thus, in our simulations the diameter of the receiving port aperture is set to 2 µm. In the following, the optical field energy entering the receiving ports can be accumulated by any miniature photodetector, for example, based on a plasmon antenna,[23] and analyzed by any discriminator circuit that compares electric signals from both switching channels.

The optical switching capabilities of various DOEs are illustrated in Figure 4a–d as the dependence of the relative transmission of the communication ports (S-parameter) $S=\log_{10}(E_1/E_2)$ on the input light wavelength λ. Here, $E_{1,2}=\int_{\Sigma 1,2}|E|^2 d\sigma$ is the intensity integral over the cross-sectional area $\Sigma_{1,2}$ of the corresponding receiving port. The absolute extrema on these curves can be attributed to the alternate (toggle) states of the photonic switch, when the signal from the first port S_1 (state "1"), or the signal from the second port S_2 (state "2") prevails. In the Figure 4, such states are marked with circles of different colors. The signal difference (S_1–S_2) can serve as a measure of the optical isolation (decoupling) of the switching channels.

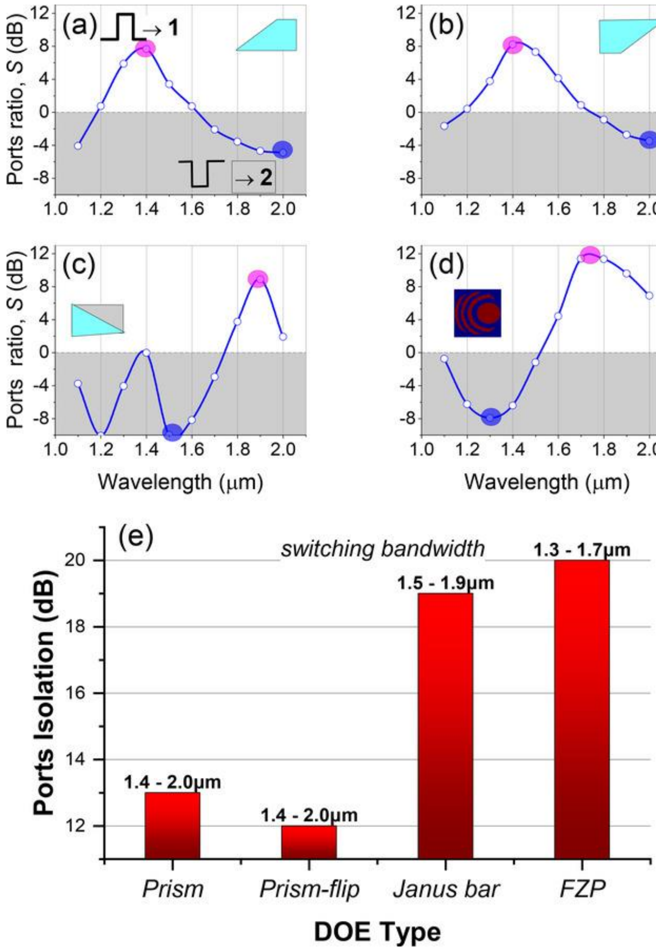

Figure 4 a–d) Relative integral transmittance of the switching ports versus input optical wavelength for prism (a), flipped prism (b), Janus bar (c), and off-axis FZP (d). e) Maximum optical isolation of different photonic switches. The numbers above bars show the switching bandwidth of the switches.

As seen, for each of the considered photonic structures with the asymmetrically optical properties there is a specific range of input wavelengths where the reliable switching can be realized at one of the optical ports. The optical isolation of the switching channels also differs depending on the types of DOE. For convenience this parameter is plotted in a separate Figure 4e, which shows that the best isolation of the switched channels is achieved using photonic switches based on a Janus bar and off-axis FZP. Here, the optical isolation can reach 20 dB that at the condition of an almost instantaneous response speed is a good result among the considered photonic hook-based schemes. Note, however, that the diameter of a switch based on the off-axis zone plate is approximately twice larger than the size of the Janus bar, which exhibits similar characteristics (Figure 4c). Generally, the switches based on the conventional prismatic particles exhibit lower optical isolation performance. However, their switching bandwidth is much wider and ranges for 0.6 µm, while for FZP and Janus particle it is about one and a half times narrower. Obviously, FZP could be additionally optimized for improving the optical switching. This can be done by changing the parameter of the "off-axis" position of the zone pattern, since the further the zones are from the symmetry axis, the stronger the dependence of the focus position on the wavelength. However, this imposes the additional technological challenges to wavelength-scaled FZP manufacturing.

Noteworthy, under the condition of $S \approx 0$ the discussed photonic switches begin to function as an optical splitter, since the field energies in both channels tend to be equal. In this case, due to the open nature of the considered types of optical switching, splitting losses can be substantial. For example, for the switch prototype based on the Janus bar as in Figure 1c, port 1 captures about 10% of the total optical energy scattered by the DOE. Besides, instead of an optical switch with the wavelength selection, one can use switching the spatial orientation of the photonic hook by changing the polarization of the incident radiation, as demonstrated in refs. [16, 18], but this type of optical switches is beyond the scope of this paper. Besides, the above photonic space switches could be fabricated using two photon polymerization (TPP) 3D printing and plano-convex-microsphere (PCM) lens laser nano marking technologies. [24, 25] TPP 3D printing is a technique to additively fabricate micro/nano features relying on the two-photon absorption process triggered by a focused femtosecond (fs) laser. Using this method, solidification of photoresist only occurs at the laser focus, which results in the micro/nanosized photonic wires along the laser scanning path and then DOEs, for example, prisms and Janus bar, can be created layer by layer in an additive way with high precision and a high degree of design freedom. PCM lens is a dielectric lens made up of a conventional plano-convex lens and an integrated high-index microsphere, and it can deliver a patterning resolution, that is smaller than the diffraction limit with an fs laser to produce the proposed FZP plate switch.

4. Conclusion

Our numerical FDTD simulations demonstrate the fundamental possibility of creating an all-optical two-channel wavelength-scaled space switch based on the photonic hook effect. We propose several prototypes of this optical device based on dielectric microstructures with broken symmetry of the geometric shape or optical properties (refractive index): two types of homogeneous rectangular glass prisms with different orientations, a rectangular Janus bar with different refractive indices in two halves, as well as an off-axis binary FZP. The unique property of a photonic hook is the dependence of its bending angle on the illuminating wavelength while maintaining extreme spatial localization in a sufficiently long distance. Thus, the proposed switch prototypes can be good candidates for implementing the optical switching in modern optoelectronics and miniature on-chip devices to provide outstanding performance without the aids of any micromechanical systems, non-linear materials, and electronic signal control.[23, 26] The best optical isolation of switched channels, which can be achieved for the switch prototype based on an optically contrast Janus particle with the linear dimensions of the order of $(6\lambda)3$, is about 20 dB in the near-IR wavelengths range including the telecom windows. It should be emphasized that in this work, only a proof-of-concept for all-optical miniature photonic hook switching is presented, and we do not carry out a full-scale optimization of the switch characteristics.

Worthwhile noting, due to the simple design of the wavelength-scaled switching element (a DOE), the high-precision 3D printing technologies such as TPP and SLA [24, 25, 27, 28] can be used to manufacture the considered mesoscale elements operating in the optical or THz spectral ranges.[29]

The potential fields of the application of the considered effect are wavelength-selecting photonic hook beam steering in biomedical applications and optical tweezer,[30] surface modification [31] using curved optical beams with wavelength-tunable characteristics for the advanced material processing, and fabrication. [32, 33]

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors were involved in simulation, results discussion, and data analysis. I.V.M. and O.V.M. were involved in conceptualization. Y.E.G. was involved in simulation. Y.E.G., O.V.M., and I.V.M. were involved in paper writing. All the authors have given approval to the final version of the article.