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Transparent Dielectric Metasurfaces for Spatial Mode Multiplexing

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Expanding the use of physical degrees of freedom to employ spatial multiplexing of data in optical communication is considered to be the most disruptive and effective solution for meeting the capacity demand of the growing information traffic. Development of space division–multiplexing methods stimulated research on spatial encoding, detection, and processing of data, attracting interest from various fields of science. Here a passive all-dielectric metasurface with near-unity transmission is demonstrated that engineers spatial mode profiles, potentially of an arbitrary complexity. The broadband response of the metasurface covers all S, C, and L bands of fiber communications. Unlike conventional phase plates, the metasurface allows for both phase and polarization conversion, providing full flexibility for the mode engineering. The dielectric metasurface is employed for mode multiplexing in a free-space optical communication system with an extinction ratio in excess of 20 dB over the whole C-band with negligible penalty even for 100 Gb s^{-1} data transmission. These results merge two seemingly different fields, *optical communication* and *metamaterials*, and they suggest a novel approach for an ultimate miniaturization of mode multiplexers and advanced LiFi technologies.

Optical communication is rapidly approaching the limits of its current technologies to cope with the fast-growing demand on capacity from the existing and emerging applications and broadband services. Over the past 40 years, the amount of information transferred over optical communication networks has been increasing by approximately an order of magnitude every 4 years and by now has long surpassed the Zettabyte per year.[1,2] The key to increase information capacity was light modulation and multiplexing across four physical dimensions: time, wavelength, polarization, and quadratures (amplitude and phase modulation). However, the achievable data transmission rates of the existing single-mode fiber transmission technologies are reaching their limits, due to the nonlinear propagation effects, saturating available capacity.[3]

Capacity is proportional to the number of independent communication channels. Therefore, a promising and feasible way to overcome the foreseeable capacity crunch is to look beyond the four physical dimensions used for light modulation and multiplexing. Electromagnetic fields can be discriminated across a fifth dimension: space. The spatial dimension can be exploited by sending information over several parallel spatial paths. This concept is widely used in other communication areas, such as printed circuit boards, Ethernet cables, multiantenna techniques in cellular wireless systems, etc. Similar techniques have been employed for free-space data transmission based on orbital angular momentum multiplexing.[4–7] Recently, optical communication research has focused on fibers that allow for spatial division multiplexing (SDM) in terms of mode division multiplexing.[1,2] A number of technical challenges have to be overcome before SDM will become a technology of choice. In particular, new solutions for control and manipulation of spatial modes are of high practical interest. Promising and potentially ground-breaking technological opportunities are opened up by the integration of metamaterials (artificial electromagnetic media structured on the subwavelength scale) with fibre-optics devices.

In this paper, we demonstrate a way towards miniaturization and integration of mode multiplexers and demultiplexers by using transparent dielectric metasurfaces: ultra-thin patterned structures that emerged as a type of *planar functional metadevices*[8] capable of reshaping and controlling the wavefront of incident light.[9] The broadband operation of metasurfaces allows to fully cover spectral ranges of several fiber communication bands. Importantly, a single metasurface may have several different functionalities for different polarizations,[10,11] different angles of incidence,[12] or/and spatial coordinates of the incident beam. This makes metasurfaces perfect candidates for SDM that

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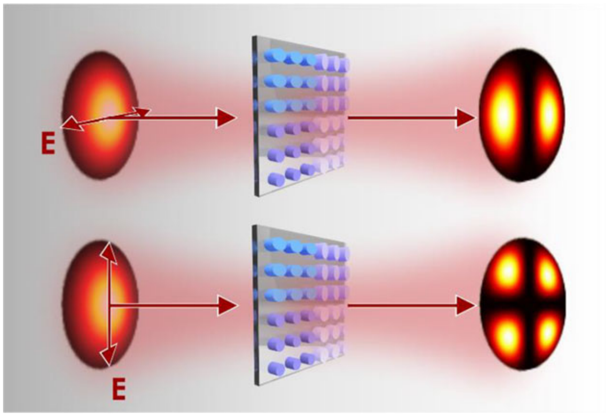

Figure 1. Concept of the mode multiplexing in spatial domain with metasurfaces. An all-dielectric metasurface of submicron thickness and near-unity transmission efficiency converts incoming Gaussian LP01 modes into LP11 and LP21 modes, enabling mode multiplexing.

relies on conversion of several incident beams into different fiber modes.

Here we design a metasurface that engineers LP fiber modes—a standard mode basis for fiber communications. We experimentally demonstrate a highly efficient simultaneous conversion, and thus multiplexing of LP01 modes into LP11 and LP21 modes in a free-space optical communication configuration as schematically shown in **Figure 1**. The approach can be readily extended to higher-order modes. With this, we suggest a novel way for miniaturized mode conversion and multiplexing in optical SDM systems.

Metasurfaces are composed of subwavelength elements that are distributed spatially across a surface. Due to resonant scattering, each element can alter the phase, amplitude, and polarization of the incoming light. Many designs and functionalities of metasurfaces suggested so far are based largely on plasmonic planar structures;[13] however, most of these metasurfaces demonstrate low efficiencies in transmission due to losses in their metallic components. In contrast, all-dielectric metasurfaces are based on lattices of subwavelength resonant dielectric elements[14] that allow avoiding absorption losses, enhancing substantially the overall efficiency of planar metaoptics[15–20] making all-dielectric metasurfaces a promising platform for diverse applications in optical communications.

We employ the approach suggested earlier in refs. [17,18] based on the generalized Huygens' principle and design a passive all-dielectric metasurface of submicron thickness and high transmission efficiency. Generalized Huygens' metasurfaces were demonstrated to act as efficient transparent phase holograms of high complexity,[18] and therefore they can be readily designed and fabricated as converters between arbitrary spatial modes. We demonstrate a single metasurface that acts as two independent phase masks for two different incident beams. For the proof-of-principle demonstration, we employ beams that differ by polarization, while, as mentioned earlier, other methods for multiplexing can be employed as well.[10–12] We exemplarily demonstrate the conversion of a Gaussian LP01 mode into a LP11 or LP21 mode depending on the LP01 polarization state.

To design the metasurface mode converter and multiplexer, we use CST Microwave Studio (see details in Section 1, Supporting Information). We employ a set of three different silicon nanopillars arranged into four quadrants (see **Figure 2**). All nanopillars have a height of 850 nm and they are placed on a fused silica substrate. Nanopillars in quadrants A have elliptical cross section with axes 215 × 140 nm. Quadrant B is composed of identical nanopillars rotated by 90°. Quadrants C and D are made of circular nanopillars with radii 180 and 150 nm, respectively. To fabricate this dielectric metasurface, we deposit silicon on a silica wafer with low-pressure chemical vapor deposition. Electron beam lithography defines the geometry of the nanopillars and reactive ion etching translates the geometry into silicon (see Figure 2a,b for the fabricated metasurface, and Section 2, Supporting Information for the fabrication details). It is worth mentioning that while the electron beam lithography is our technique of choice for its flexibility, the metasurface design is readily suitable for fabrication with other techniques, including nanoimprinting lithography, allowing for a scalable low-cost production. All the quadrants show high optical transmission over the spectral region of the C, S, and L optical fiber communication bands. Experimentally measured transmission spectra are shown in Figure 2c.

Figure 2d shows the experimentally measured phase profiles of the metasurface for two linear orthogonal polarizations at 1550 nm wavelength (see details in Section 3, Supporting Information). The design parameters are optimized to provide π phase delay difference between the arrays C and D. The quadrant A provides the same phase delay as the quadrant C for the horizontal polarization and the same delay as the quadrant D for the vertical polarization. The phase delay of the quadrant B is π-shifted from that of the quadrant A and, correspondingly, it is the same as for quadrant C for the vertical polarization, as well as for quadrant D for the horizontal polarization. Thus, the metasurface serves as a *phase mask* that converts horizontally polarized Gaussian LP01 mode into LP11b mode and vertically polarized Gaussian mode into LP21a mode. Figure 2e presents the experimentally observed mode conversion at 1550 nm.

In the following portions, we report on the metasurface performance in fiber telecommunication setup. We directly compare the performance of the metasurface with conventional phase plates.[21] As the phase plates can convert between pairs of modes only (e.g., LP01 → LP11 or LP01 → LP21), two phase plates are used in the experiments. **Figure 3**a schematically shows the experimental setup, and the details can be found in Section 4, Supporting Information. A standard single-mode fiber (SMF-28) is used at the input, and the light from the fiber collimated by a lens passes through the metasurface. The diameter of the collimated beam (0.3 mm) is substantially smaller than the size of the metasurface (1.5 mm). To allow the simultaneous measurement of the LP11-mode and LP21-mode, we used a beam splitter after the metasurface, and selective phase plates LP11 and LP21 correspondingly. Finally, the two demultiplexer modes were coupled back into fibers. We note here that while the current setup arrangement includes the metasurface along with conventional bulky optics components (e.g., lenses and a beam splitter), the metasurface platform allows to further integrate standard elements into a single optical component. Indeed, in the past we have seen demonstrations of metasurfaces combining functionalities of a lens and a beam deflector, or a lens and a polarization converter.[16] Thus, a single metasurface

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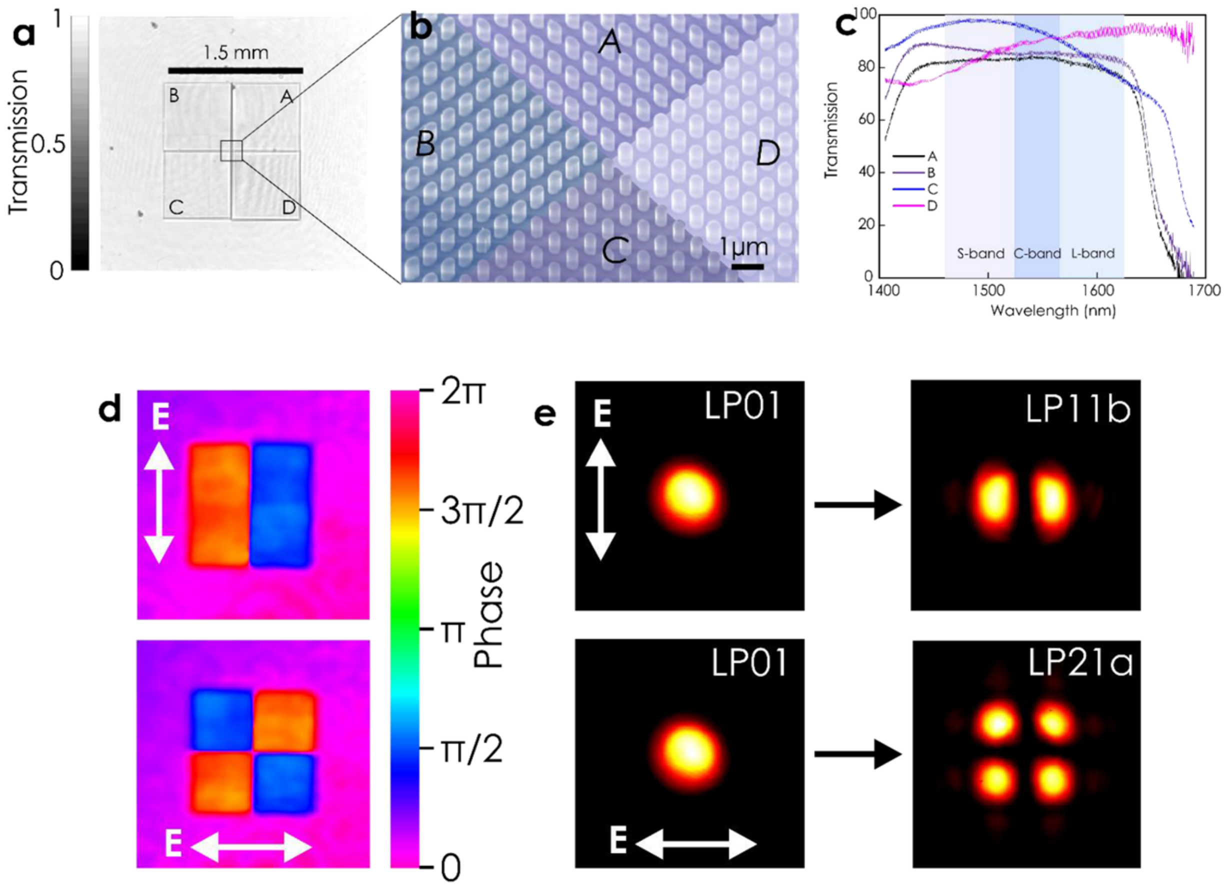

Figure 2. a) Image of the metasurface multiplexer in an optical transmission microscope. Illumination spectral range is 1530–1560 nm. b) SEM image of a central part of the metasurface. c) Experimentally measured transmission spectra of the four quadrants of the metasurface. d) Experimentally measured phase accumulation across the metasurface for vertically and horizontally polarized lights. e) Experimentally observed mode conversion: (top) vertically polarized LP01 → LP11b and (bottom) horizontally polarized LP01 → LP21a.

can combine functionalities of beam collimator, mode converter, and beam deflector if necessary. In addition, provided that metasurfaces can be directly fabricated on optical fiber facets,[22] they allow for ultimate miniaturization and integration of the spatial mode multiplexing/demultiplexing setups.

We first compare the purity of mode conversion with that of the conventional phase plates. For this we experimentally retrieve the extinction ratio—the ratio between the two levels of intensities corresponding to binary "1," and binary "0" for each of the two spatial modes. The metasurface extinction ratio was measured to be higher than 22 dB, similar to that of the two conventional phase plates used for the two modes demultiplexing (25 dB) (see details in Section 4, Supporting Information).

Next, we study the impact of the metasurface on the error rate in the information channel. For this we send 100 Gb s^{-1} data stream to the input of the mode multiplexer. The data at the input is polarization-multiplexed, and the metasurface performs the conversion into mode multiplexed 100 Gb s^{-1} data stream.

The performance of digital communication systems is measured in bit-error rate (BER)—number of bits received with errors to the total number of the transmitted bits. In is customary in the communication engineering to measure system performance in dB. For that purpose, BER is converted in the so-called Q factor, defined as

$$Q^2\ [\mathrm{dB}] = 20\log_{10}\left(\sqrt{2}\,\mathrm{erfc}^{-1}\,[2\,\mathrm{BER}]\right)$$

where "erfc" stands for error function. We experimentally retrieve the signal BER of our system that once compared with the BER of a conventional system using phase plates indicates the overall probability of bit error in information transfer arising due to the mode multiplexing through ours metasurface device. We perform these measurements over the whole spectral C-band of fiber communications, and see only a negligible performance fluctuation (<0.1 dB) over the C-band demonstrating its potential to handle fully loaded wavelength-division multiplexing (WDM) systems (≈90 frequency channels) for the ultimate increase of the capacity of fiber networks. The results are shown in Figure 3b (more details and data can be found in Section 4, Supporting Information).

We would like to stress that the proposed concept can be readily transferred to other material platforms.[23] This, in particular, would allow to approach other spectral ranges where material properties of silicon are not favorable, including visible light communications (or LiFi) that exploits the ability to modulate visible

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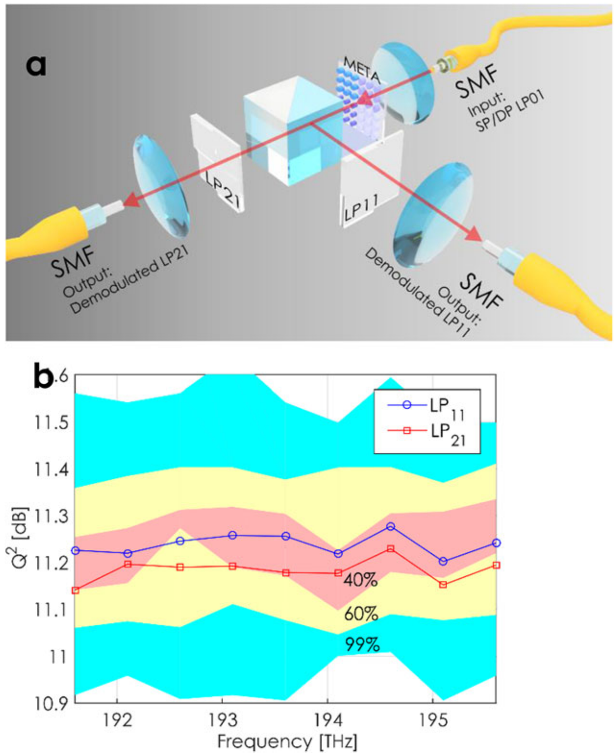

Figure 3. a) Experimental apparatus for the assessment of the metasurface mode multiplexer performance. b) Q factor as a function of channel frequency over the C-band with a mechanical alignment for 193.6 THz. The colored lines show the Q factor averaged over 20 repetitions for the two modes correspondingly. The colored surfaces identify the area containing the Q factor values with a probability of 40, 60, and 99%.

LEDs at high speed for wireless communication applications,[24] and transmit parallel data streams scaling up the data capacity by spatial multiplexing and high-level modulation schemes.[25]

We have suggested a novel type of metadevice multiplexers made of all-dielectric metasurfaces which allow to design mode profiles of arbitrary complexity, including the Eisenbud–Wigner–Smith states[26] and modes with an orbital angular momentum.[5] We have demonstrated, for the first time to our knowledge, that highly transparent all-dielectric metasurfaces can be employed for engineering the mode profiles with high efficiency over a broadband spectral range covering telecommunication S, C, and L bands. We have realized experimentally the conversion of LP01 modes into LP11 and LP21 modes for a free-space optical communication system. In this way, we have confirmed that a single metasurface is capable of mode multiplexing with an extinction ratio in excess of 20 dB over the C-band with negligible penalty even for 100 Gb s^{-1} data transfer signals. The metasurfaces introduce no performance degradation except for an excess loss due to reflections which can be minimized by applying an antireflective coating. Finally, we have shown that this type of metadevice is capable of mode-multiplexing operation while previously one required two phase plates with increased free-space arrangement requirements and bulkiness, suggesting a novel approach for ultimate miniaturization of mode multiplexers and advanced LiFi technologies. We notice that in conjunction with polarization modulator, the metasurface provides a unique capability of ultrafast mode modulation, thus enabling to encode information into the spatial domain. The ability to both multiplex and modulate information by using spatial modes fully opens the potential of the spatial dimension as a degree of freedom in the next generation optical transmission systems for both free space and fiber communications. It was predicted in ref. [27] that the extension of the current trends in global communications to ≈2030 and 2035 would, respectively, require systems with an increased number of parallel spatial paths. Therefore, spatial parallelism and the development of SDM × WDM systems are unavoidable requirements. It was also stressed that a substantial research progress will have to take place across multiple areas, from system architectures to digital signal processing to integrated-optics arrayed device designs in order to avoid an otherwise imminent optical networks capacity crunch. We do believe that metasurfaces offer conceptually new designs for the fundamental building blocks of future systems that will represent a substantial advance in communication technology.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

metasurfaces, nanophotonics, optical communications, space division multiplexing

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