Airy beam induced optical routing

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We present a new all-optical routing scheme based simultaneously on optically induced photonic structures and the Airy beam family. The presented work utilizes these accelerating beams for the demonstration of an all-optical router with as many as 16 individually addressable output channels. In addition, we are able to activate multiple channels at the same time providing us with an optically induced splitter with configurable outputs.

Discrete photonic structures are part of the vision to overcome the unavoidable bandwidth constraints of electronics by heading towards an all-optical computing architecture. In this work, we present a new scheme for the spatial routing of light based on optically induced photonic structures.

During the last decade, the optical induction technique [1] got a lot of attention. This approach allows for the preparation of a multitude of linear and nonlinear refractive index schemes by illuminating a photorefractive material with structured intensity distributions. Over the years, the achievable lattice complexity developed from fundamental one- and two-dimensional patterns [2,3] to three-dimensional quasi-crystals [4] and even the multiplexing of arbitrary structures [5] is possible nowadays.

In this respect, optically induced complex two-dimensional structures are particularly interesting since they require a modulation in the transverse dimensions but remain invariant in a third direction. Certainly, the inducing intensity distribution has to fulfill this requirement as well. While this at first seems to contradict the ubiquitous diffraction, Durnin et al. demonstrated the realization of such a nondiffracting beam in 1987 [6] and his discovery today is called Bessel beam. Besides Bessel beams, other families of nondiffracting beams were discovered over the years and now it is well-known that four different families – Bessel, Mathieu, Weber, and discrete nondiffracting beams – exist [7,8]. Moreover, we recently demonstrated that all these different families can even be used for the optical induction of corresponding photonic lattices [9].

In addition to these classical nondiffracting beams, the related class of accelerating beams [10] is a field of vivid research as well. During propagation, the intensity distribution of an accelerating beam retains its shape but it is shifted in the transverse plane leading to an overall accelerated propagation trajectory. Based on solutions to the Schrödinger equation found by Berry and Balazs [11], the first accelerating optical beam was described and realized in...
This so-called Airy beam has already been utilized for many different applications ranging from abruptly autofocusing waves \cite{14} to optical snowblowers in micromanipulation experiments \cite{15}. Moreover, recent works introduced new ideas for controlling the trajectory of accelerated beams \cite{16-19} and some of them support even arbitrary paths \cite{20,21}.

In the following, we introduce an all-optical routing technique based on these beams. The underlying experimental setup is schematically shown in Fig. 1. The beam from a frequency-doubled Nd:YAG laser at a wavelength of 532 nm is divided into two separate beams and each of them illuminates a programmable spatial light modulator (SLM). The first modulator (SLM 1, see Fig. 1) is used to imprint a cubic phase onto the incident beam. In combination with a Fourier transforming lens, this leads to the generation of a two-dimensional Airy beam \cite{13} at the front face of the depicted 20 mm long photorefractive Sr_{0.6}|Ba_{0.4}|Nb_{2}O_{6} (SBN:Ce) crystal. The crystal is externally biased with a dc electric field directed along its optical axis in order to allow the optical induction of a corresponding refractive index distribution. Furthermore, we can illuminate the crystal homogeneously with a white light source to erase any written refractive index configuration. Using a technique similar to the one described in \cite{22}, the second SLM (cf. Fig. 1) generates and positions a Gaussian input for the optically induced router. Finally, an imaging lens and a camera mounted on a translation stage can be used to analyze the intensity distribution in different transverse planes.

The propagation characteristics of a two-dimensional Airy beam generated in the described setup are summarized in Fig. 2. The cubic phase spectrum put on the first SLM is shown in Fig. 2a. After the Fourier transforming lens, we get the two-dimensional Airy beam depicted in Fig. 2b at the front face of the crystal. The beam propagates through the photorefractive material and at the crystal’s back face we observe the shifted two-dimensional Airy pattern shown in Fig. 2c. While the outer Airy lobes already show some diffraction, the beam maximum is still extremely pronounced. Figure 2d illustrates the accelerated propagation dynamics in the longitudinal direction and emphasizes the undisturbed parabolic propagation of the Airy beam maximum.
Figure 2. Two-dimensional Airy beam. (a) Cubic phasespectrum, (b) experimentally observed Airy beam intensity distribution at the front face and (c) at the back face of the crystal, (d) accelerating intensity profile in longitudinal direction. The green lines in (b) and (c) mark the longitudinal plane shown in (d). Besides (a) all figures are normalized.

Since in our setup the Airy beam generation is based on a computer-controlled SLM, we can easily change the propagation characteristics. On the one hand, we can rotate the whole structure by simply rotating the phase pattern (cf. Fig 2a) on the SLM. On the other hand, a stretching or compression of the cubic phase distribution leads to a change in the Airy beam’s acceleration and therewith to different transverse shifts between the input position of the maximum at the front face and the output position at the back face of the crystal. Figure 3 shows that in this way a combination of just four different orientations with four accelerations provides already 16 distinct output channels accessible from a single input position.

In Fig. 3a, the input position of an Airy beam turned by 90° with respect to the configuration shown in Fig. 2 is marked with a cross. Figures 3c–3f then highlight the variable shift between this input position and the output position of the Airy beam at the back face of the crystal provided by different beam accelerations. Combining these four curvatures with four 90° beam rotations gives us the configuration of possible outputs shown schematically in Fig. 3b.

If now the external dc field is applied to the photorefractive medium, the optical induction leads to a reversible refractive index modulation inside the material according to the incident intensity distribution. In this way, we get a curved path of increased refractive index going from the input position at the front face to the corresponding output at the back by illuminating with one of the discussed Airy beams. Using the homogeneous white light illumination, the induced structure can be erased again and the system is prepared for the optical induction of a new input-output configuration.

Next, we generate a Gaussian probe beam as an input to our system (cf. Fig. 4a). Without an optically induced structure, the Gaussian beam diffracts and leads to the broadened output at the back face of the crystal shown in Fig. 4b. However, if an Airy beam induced refractive
Figure 3. Output scheme of the Airy beam induced optical router. (a) Input position of the Airy beam at the front face of the crystal, (b) schematic array of 16 output channels given by four 90° beam rotations and four different accelerations each, (c), (d), (e), (f) output position of the Airy beam at the back face of the crystal for different accelerations. Besides (b) all figures are normalized.

index channel is present, we observe a precisely guided beam at the addressed output position. Figures 3b–3f illustrate this for three arbitrarily chosen channels.

Furthermore, we can apply the idea of incremental multiplexing of optically induced structures [24] in order to activate multiple output channels at the same time. Utilizing the computer-controlled SLM, our approach is capable of inducing refractive index structures that simultaneously guide light from one input to multiple selected outputs by continuously switching between different Airy beam configurations faster than the time constants of the medium. Figure 3f demonstrates this unique feature for a two-channel splitter that guides the input signal (cf. Fig. 3a) to two arbitrarily chosen outputs.

In summary, we introduced an all-optical routing setup based on Airy beams. The demonstrated results show a reconfigurable photonic router with as many as 16 individually addressable output channels. In addition, multiple channels can be activated at the same time providing an optically induced splitter with configurable outputs as well.

Since the optically induced guiding structure can also be used with wavelengths other than the inducing one [25], our technique even allows for the all-optical routing of wavelength- multiplexed signals and the channel addressing can be done using different spectral regions as well. Combined with novel ideas for controlling the trajectory of accelerated beams [17, 19–21] our presented routing concept can facilitate very complex schemes, and thus we are convinced that this new approach for all-optical routing will find many significant applications.
Figure 4. Airy beam induced optical routing. (a) Gaussian input beam at front face of the crystal, (b) diffracted Gaussian output at back face of the crystal without induced refractive index structure, (c), (d), (e) guided output for different selected channels, (f) optically induced splitter with multiple selected outputs. All figures are normalized.

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