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Metal-dielectric resonator integrated in an asymmetric slab waveguide for spatiotemporal optical vortex generation

A.I. Kashapov[1,2]✉, E.A. Bezus[1,2], D.A. Bykov[1,2], L.L. Doskolovich[1,2]

[1] Image Processing Systems Institute, National Research Centre "Kurchatov Institute", Samara, Russia;

[2] Samara National Research University, Samara, Russia

✉ kashapov.ai@ssau.ru

Abstract. We theoretically and numerically demonstrate an efficient approach for generating a spatiotemporal optical vortex (STOV) in an asymmetric dielectric slab waveguide using a metal-dielectric structure constituted by several metal strips integrated into the waveguide core layer. The presented rigorous numerical simulation results fully confirm the developed theoretical model.

Keywords: spatiotemporal optical vortex, integrated optics, asymmetric dielectric slab waveguide, spatiotemporal differentiation

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Материалы конференции
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Формирование пространственно-временного оптического вихря с помощью металлодиэлектрического резонатора, интегрированного в асимметричный волновод

А.И. Кашапов[1,2]✉, Е.А. Безус[1, 2], Д.А. Быков[1, 2], Л.Л. Досколович[1, 2]

[1] Институт систем обработки изображений Курчатовского комплекса кристаллографии и фотоники Национального исследовательского центра «Курчатовский институт», г. Самара, Россия;

[2] Самарский национальный исследовательский университет им. академика С.П. Королёва, г. Самара, Россия

✉ kashapov.ai@ssau.ru

Аннотация. Предложен и теоретически и численно исследован эффективный подход для формирования пространственно-временного оптического вихревого пучка в асимметричном диэлектрическом волноводе с помощью металлодиэлектрической структуры, состоящей из нескольких металлических полос, «интегрированных» в волновод. Представленные результаты строгого численного моделирования хорошо согласуются с разработанной теоретической моделью.

Ключевые слова: оптический вихрь, интегральная оптика, ассиметричный волновод, пространственно-временное дифференцирование

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Introduction

Recently, a new class of optical vortex (OV) beams has attracted considerable research attention, namely, the so-called spatiotemporal optical vortex (STOV) beams [1–3]. In contrast to the conventional OV beams possessing a zero in the field amplitude and a screw-type phase dislocation in the plane perpendicular to the propagation direction [4], STOV beams are essentially polychromatic and carry orbital angular momentum, which is orthogonal to the propagation direction of the beam. STOV beams have many important potential applications including optical trapping, super resolution microscopy, and free-space telecommunications, among others.

Results and Discussion

Let us consider the transformation of the envelope of the H_z magnetic field component of an incident TE-polarized spatiotemporal pulse propagating in a slab waveguide occurring upon reflection from a metal–dielectric structure integrated into the waveguide (see Fig. 1, *a*). As it was shown in [5], the envelope of the reflected pulse written in the coordinate system associated with it has the form

$$\begin{aligned} P_{\mathrm{refl},H_z} = \iint f(\omega_0+\tilde{\omega}, z) G(k_y,\tilde{\omega}) TF(k_y,\tilde{\omega}) \times \\ \times \exp[-ix(k_x - n_{\mathrm{eff}}(\omega_0)\omega_0/\mathrm{c}) + ik_y y]\exp[-i\tilde{\omega}t]\mathrm{d}k_y \mathrm{d}\tilde{\omega}, \end{aligned} \quad (1)$$

where G is the spectrum of the incident pulse describing the amplitudes of the guided modes constituting it, f is the function describing the transverse field profile of the modes of the slab waveguide along the z-axis, and TF is the transfer function of the structure.

As an integrated nanophotonic element intended for the generation of an STOV in the waveguide layer, we propose to use a “three-strip” metal-dielectric structure consisting of three gold (Au) strips “buried” in the waveguide (Fig. 1, *a*). We theoretically studied the transfer function of the structure [5, 6] and obtained that in order to generate a spatiotemporal optical vortex, it is necessary for the arguments of the complex coefficients at the “spatial” and “temporal” linear terms of the transfer function of the structure to differ by $\pi/2$.

Let us consider the following example of the integrated structure for the STOV generation: a gallium phosphide (GaP) waveguide core layer with 100 nm thickness surrounded by silicon dioxide (SiO_2) substrate and free-space (air) superstrate (see Fig. 1, *a*). Using a specially developed algorithm for optimizing the structure parameters involving multiple simulations of the diffraction of TE-polarized incident modes on the structure, we obtained a structure with the following parameters satisfying the STOV generation conditions at the angle of incidence $\theta = 65°$ and the free-space wavelength $\lambda = 630$ nm: $w_1 = 25.1$ nm, $w_2 = 53.2$ nm, $w_3 = 64$ nm, $w_4 = 222$ nm, and $w_5 = 125$ nm (see Fig. 1, *a*). The numerical solution of Maxwell’s equations for the considered structure was performed using an efficient implementation of the aperiodic Fourier modal method adapted to the solution of the problems of integrated optics [7, 8]. In Fig. 1, *b*, *c*, the absolute value and argument of the numerically calculated TF of the designed structure are presented.

Figs. 1, *d*, *e* show the absolute value and phase of the numerically calculated envelope of the H_z component of the spatiotemporal pulse reflected from the structure at the central plane of the waveguide core layer for an incident optical pulse described by a Gaussian function ($\sim\exp[-t^2/\sigma_t^2 - y^2/\sigma_y^2]$, where $\sigma_t = 2.8$ ps and $\sigma_y = 14$ μm). The figures demonstrate that the reflected optical signal does indeed contain an STOV. The numerically obtained and "model" (analytically calculated) envelopes (the latter not shown here for the sake of brevity) are in excellent agreement, the normalized root-mean-square deviation between them being equal to only 0.35%. Fig. 2 shows the cross-sections of the H_z reflected pulse component, from which it can be seen that the amplitude zero at $y = 0$ and $t = 0$ is conserved for all z values. This, along with the results presented in Figs. 1, *d*, *e*, confirms the generation of an STOV in the asymmetric waveguide.

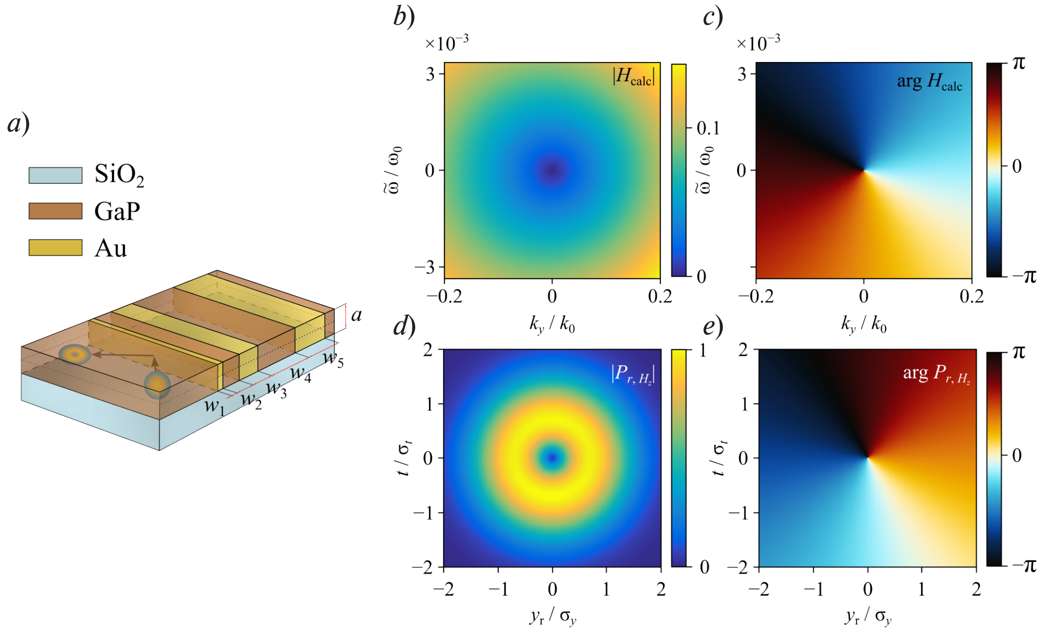

Fig. 1. Geometry of considered integrated structure and schematic depiction of generation of spatiotemporal optical vortex in asymmetric waveguide (*a*). Amplitudes (absolute values) and phases (arguments) of numerically calculated transfer function of structure ((*b*) and (*c*)) and envelope of H_z component of reflected optical pulse ((*d*) and (*e*))

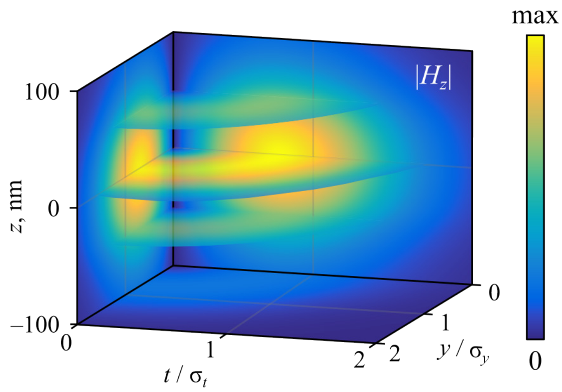

Fig. 2. Cross-sections of normalized H_z component of reflected optical pulse containing STOV

Conclusion

We theoretically studied and numerically confirmed the generation of a spatiotemporal optical vortex in an asymmetric dielectric slab waveguide. In the proposed approach, a spatiotemporal pulse containing an STOV is generated upon reflection of an incident spatiotemporal pulse from an integrated metal-dielectric structure constituted by three metal strips placed in the core layer of the waveguide. The presented results of rigorous electromagnetic simulations of the designed integrated structure fully confirmed the obtained theoretical results and demonstrated the generation of a reflected spatiotemporal optical pulse containing an STOV propagating in the asymmetric slab waveguide.

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THE AUTHORS

KASHAPOV Artem I.
ar.kashapov@outlook.com
ORCID: 0000-0002-7367-6277

BEZUS Evgeni A.
evgeni.bezus@gmail.com
ORCID: 0000-0001-7496-8960

BYKOV Dmitry A.
bykovd@gmail.com
ORCID: 0000-0002-9576-2360

DOSKOLOVICH Leonid L.
leonid@ipsiras.ru
ORCID: 0000-0001-8649-028X

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