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Generation of spatiotemporal optical vortices using Kretschmann setup for transverse magnetic and transverse electric polarizations

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Abstract. We investigate optical properties of the Kretschmann setup, which contains a dielectric prism and a metal layer and may also contain an additional dielectric layer. We show that the investigated structure allows one to generate a transverse-magnetic- (TM-) polarized spatiotemporal optical pulse comprising an optical vortex using the “conventional” Kretschmann configuration without an additional layer. We also demonstrate that in the case of transverse electric (TE) polarization, the additional dielectric layer is necessary for satisfying the optical vortex generation condition. The results of rigorous numerical simulations demonstrate the possibility of generating spatiotemporal optical vortices with high quality for both TM- and TE-polarizations.

Keywords: Kretschmann setup, optical vortex, optical computing

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Материалы конференции
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Формирование пространственно-временных оптических вихрей с помощью схемы Кречмана для поперечной магнитной и поперечной электрической поляризаций

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Аннотация. В работе исследуются оптические свойства схемы Кречмана, которая содержит диэлектрическую призму и металлический слой, но также может содержать дополнительный диэлектрический слой. Показано, что исследуемая структура позволяет формировать пространственно-временной оптический импульс с поперечной магнитной (ТМ-) поляризацией, содержащей оптический вихрь, используя «классическую» схему Кречмана без дополнительного слоя. Также показано, что в случае поперечной электрической (TE) поляризации дополнительный диэлектрический слой необходим для выполнения условия формирования оптического вихря. Результаты строгого численного моделирования демонстрируют возможность формирования пространственно-временных оптических вихрей с высоким качеством для TM- и TE-поляризаций.

Ключевые слова: геометрия Кречмана, оптический вихрь, оптические вычисления

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Introduction

Spatiotemporal optical vortex pulses (STOV pulses) are a special type of optical signals that have unique properties and are promising for applications in various fields of science and technology. These pulses are defined by the presence of a zero in the amplitude and a discontinuity in the phase in the spatiotemporal domain, which results in an unusual ‘doughnut-shaped’ spatiotemporal field distribution. Prospective applications of STOV pulses are in such fields as optical communications, optical trapping, and micromanipulation [1–3]. In this regard, active research and development of new methods for STOV generation are ongoing [4–5]. In the present work, the possibility of generating TE- and TM-polarized STOVs using a simple differentiating structure corresponding to the Kretschmann setup is investigated.

Materials and Methods

The method of generating an STOV using a photonic structure performing analog optical differentiation (see the inset in Fig. 1) has been previously studied in [5–7], including the previous works of the present authors [6, 7]. The key issue in generating an STOV with a differentiating structure is the proper selection of the parameters of such a structure. As it was shown in [6, 7], the structures generating STOVs are a subset of differentiating structures having a transfer function (TF) H_{st} (which describes the transformation of a spatiotemporal optical pulse by the diffractive structure) of a special form. Namely, in the vicinity of the operating spatial ($k_{x,0} = k_0 n_s \sin\theta$) and angular ($\omega_0$) frequencies, the TF has to be proportional to their weighted sum with coefficients c_x and c_t: $H_{st}(k_{x,\mathrm{inc}},\omega_{\mathrm{inc}}) \approx c_x k_{x,\mathrm{inc}} + c_t\omega_{\mathrm{inc}}$, where $\omega_{\mathrm{inc}} = \omega - \omega_0$, $k_{x,\mathrm{inc}} = k_0 n_s \sin\theta_{\mathrm{inc}}$, and θ_{inc} is the ‘local’ angle of incidence in the coordinate system associated with the incident optical pulse. It is worth noting that the differentiating structure possesses a reflection zero at $k_x = k_{x,0}$ and $\omega = \omega_0$ (i.e., at $k_{x,\mathrm{inc}} = 0$ and $\omega_{\mathrm{inc}} = 0$). In [6], the following condition for the STOV generation by differentiating structures was obtained:

$$\arg c_x - \arg c_t = \pm\pi/2. \tag{1}$$

The structure studied in this work for generating TE- and TM-polarized STOVs is a structure corresponding to the Kretschmann configuration, but optionally possessing an additional dielectric layer, hereafter referred to as the generalized Kretschmann setup (see the inset in Fig. 1). The parameters of the investigated structure, such as the thickness of the metal (h_{met}) and dielectric (h_c) layers, can be calculated for each pair of the wavelength λ (or the angular frequency ω_0) and the angle of incidence θ (or the in-plane wave vector component $k_{x,0}$) using the algorithm described in [7].

The materials used in the studied structure are SF11 glass (prism), gold (Au) (metal layer), and silicon dioxide (SiO_2) (dielectric coating). The structure is located in air (free space) with refractive index $n_s = 1$. It is also important to note that the dispersion of the listed materials was taken into account in the numerical simulations. The dispersion data were taken from [8].

Results and Discussion

First, let us consider the generation of a TM-polarized STOV. As it was previously noted, the layer thicknesses h_{met} and h_{c} (see the structure in the inset in Fig. 1) are determined from the condition of obtaining a reflection zero at the central wavelength λ and the angle of incidence θ. The structure found in this way provides optical computation of the temporal derivative of the envelope of an incident pulse or of the spatial derivative of the profile of an incident beam (or works as a frequency or a spatial optical filter). It is convenient to find a structure that satisfies the condition of STOV generation (1) by considering the dependence of the difference of arguments of the coefficients c_x and c_t on wavelength and angle of incidence. Fig. 1,*c* shows this dependence for the case of TM-polarization, and Fig. 1,*a* and 1,*b* show the corresponding layer thicknesses h_{met} and h_{c} of such structures. Let us note that the angle of incidence and wavelength ranges are chosen in such a way that the area, in which the STOV generation condition is fulfilled, is clearly visible. The solid white line in Fig. 1,*b* indicates the condition $h_{\mathrm{c}} = 0$, i.e., shows the structures corresponding to the conventional Kretschmann setup without an additional layer. It is important to note that the crosshatched area denotes the region, in which the calculated thicknesses of the dielectric coating are negative. In this case, according to the formulas presented in [7], the value π/k_z can be added to the dielectric layer thickness to make it positive, where k_z is the z-component of the wave vector in the dielectric layer. The dotted black line in Fig. 1,*c* shows, where the STOV generation condition is met, and the solid black line repeats the line in Fig. 1,*b*, where $h_{\mathrm{c}} = 0$. Therefore, we can see from Fig. 1 that there exist structures in the conventional Kretschmann

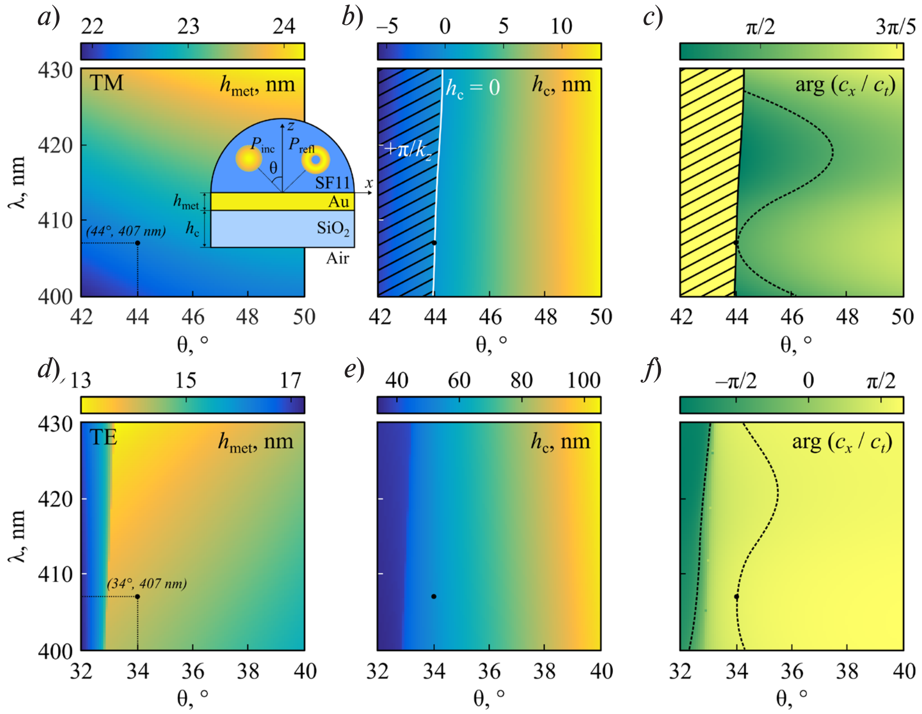

Fig. 1. Thicknesses of the metal and the dielectric layers of the studied structure, and the quantity arg (c_x/c_t), considered as functions of wavelength and angle of incidence, at which zero reflection is obtained (*a*, *b*, *c* and *d*, *e*, *f* for TM- and TE-polarizations, respectively); dotted lines in (*c*), (*f*) show, where the STOV generation condition is met; solid lines in (*b*), (*c*) show the structures in the conventional Kretschmann configuration ($h_{\mathrm{c}} = 0$); black dots indicate the parameters of the structures considered in the examples. The inset shows the geometry of the structure

configuration that enable the STOV generation in reflection. Further, we will consider the example of the structure marked by the black dot in Fig. 1, *a*, *b*, *c* ($\lambda = 407$ nm, $\theta = 44°$, $h_{\text{met}} = 22.4$ nm).

Next, we will carry out a similar study for the case of TE-polarization. In order to do this, the structures in the generalized Kretschmann configuration were also calculated as shown in Fig. 1, *d, e, f*. However, it should be noted that in this case, the condition of STOV generation is achievable only in the presence of an additional dielectric coating (see Fig. 1,*e*), in contrast to the case of TM-polarization. Let us also note that during the process of material selection for the studied structures in the generalized Kretschmann configuration, other common materials (e.g., BK7 and BAF10 glasses for the prism, Ag and Cu for the metal layer, and Al_2O_3 for the dielectric coating) were considered. However, a combination of materials providing the STOV generation in the case of TE-polarization at zero thickness of the dielectric coating could not be found. Indeed, in the case of TM-polarization, the effect of zero reflectance at zero thickness of the dielectric coating is caused by the excitation of a surface plasmon polariton at the so-called critical coupling condition [9], which, obviously, cannot be achieved in the case of TE-polarization without an additional dielectric layer. For the example considered below, the structure marked with the black dot in Fig. 1, *d*, *e*, *f* ($\lambda = 407$ nm, $\theta = 34°$, $h_{\text{met}} = 15.9$ nm, $h_{\text{c}} = 54.3$ nm) was chosen.

Consider an example of the structure indicated by the black dots in Fig. 1, *a*, *b*, *c*, which generates a TM-polarized STOV. Fig. 2, *a*, *d* show the amplitude and phase of the TF of the investigated structure, from which it is clear that the TF can be well approximated by the TF of an 'ideal' differentiating filter $H_{\text{st}}(k_{x,\text{inc}},\omega_{\text{inc}}) = c_x k_{x,\text{inc}} + c_t \omega_{\text{inc}}$, and the condition (1) is fulfilled with a high accuracy. This is confirmed by Fig. 2, *b*, *c* and Fig. 2, *e*, *f*, which show the amplitude and phase of the reflected pulse envelope calculated numerically using the method [10], and the corresponding 'model' (analytically calculated) function [6, 7]. The root-mean-square error (RMSE) of the above mentioned magnitudes, normalized by the maximum amplitude of the reflected pulse, is only 0.17%.

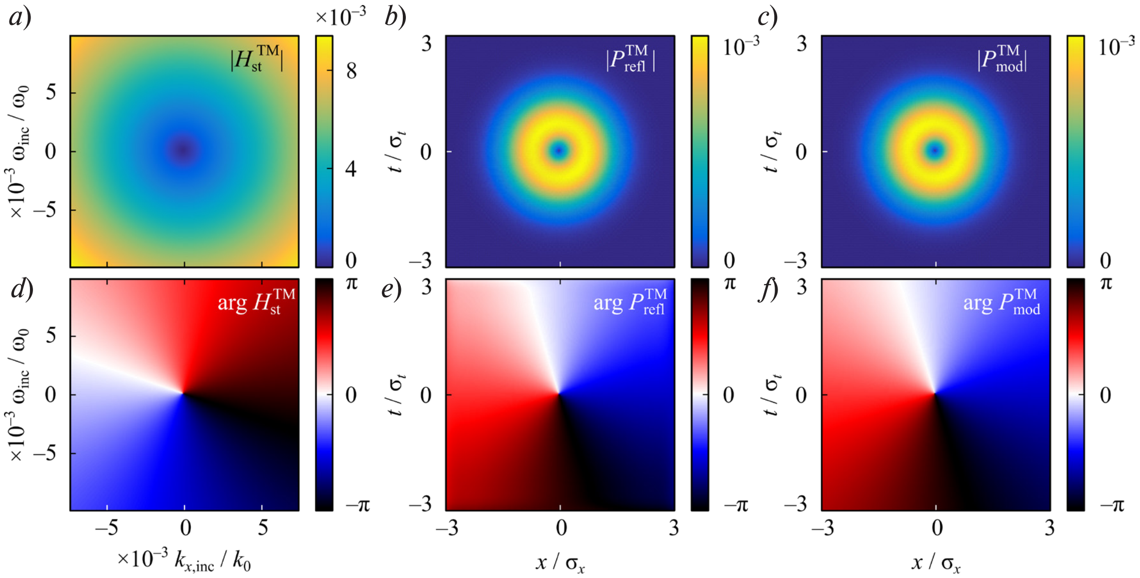

Fig. 2. Amplitudes (*a*) of the transfer function of the structure in the conventional Kretschmann configuration generating a TM-polarized STOV, (*b*) of the envelope of the reflected spatiotemporal optical pulse calculated numerically, (*c*) of the model function [6, 7], and their arguments (*d*), (*e*), (*f*), respectively

Next, we consider an example of the generalized Kretschmann setup generating a TE-polarized STOV. The parameters of the structure were previously shown in Fig. 1, *d*, *e*, *f* by black dots. The TF of this structure is visually very similar to the TF of the structure considered in the previous example, so, for the sake of brevity, we do not show it in Fig. 3. At the same time, it is worth mentioning that the TF of this structure is also well approximated by the TF of an ideal differentiating filter. Fig. 3 shows the amplitude (Fig. 3,*a*) and phase (Fig. 3,*b*) of the reflected

TE-polarized spatiotemporal optical pulse envelope. Comparing the results of the numerical simulation with the model function in the same way as in the example above, we obtained that the normalized RMSE of the amplitude of the numerically calculated reflected pulse envelope from the model function amounts to 0.4%.

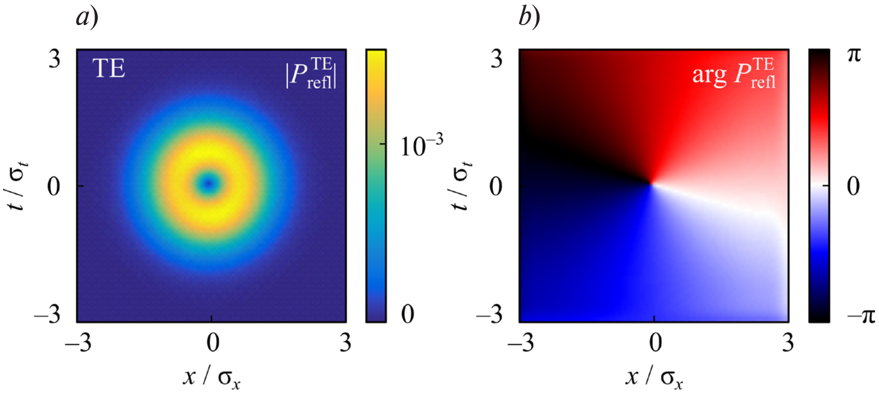

Fig. 3. Amplitude (*a*) and phase (*b*) of the reflected TE-polarized spatiotemporal optical pulse envelope

Conclusion

In this work, we investigated the Kretschmann configuration with an additional dielectric layer (generalized Kretschmann setup) enabling the generation of TM- and TE-polarized spatiotemporal optical vortex pulses. It was obtained that in the case of TM-polarization, it is sufficient to use the structure in the conventional Kretschmann geometry without an additional layer, whereas in the case of TE-polarization, the condition of optical vortex generation can be achieved only when an extra dielectric layer is added. The results of numerical simulations demonstrated a high quality of optical vortex generation by the investigated structure: in both cases (TM- and TE-polarizations), the values of the normalized root-mean-square error do not exceed 0.5%. The obtained results are promising for application in new optical communication and optical computing systems.

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