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# INFLUENCE OF A TWIST DEFECT IN A LAYERED HELICAL CORE FIBER ON SINGLE-CHARGED OPTICAL VORTEX GENERATION

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It has been described how twist defect in a layered helical core fiber acts on generation of optical vortex with unity topological charge from the fundamental mode. Influence of the twist defect is maximal when it is located right in the middle of the fiber and leads to suppression of optical vortex generation. In addition it has been established that impact of twist defect is negligibly small if it is located near the ends of the fiber, which has the length equal to a zero order conversion length.

***Keywords***: optical vortex, helical core fiber, optical fiber.

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## INTRODUCTION

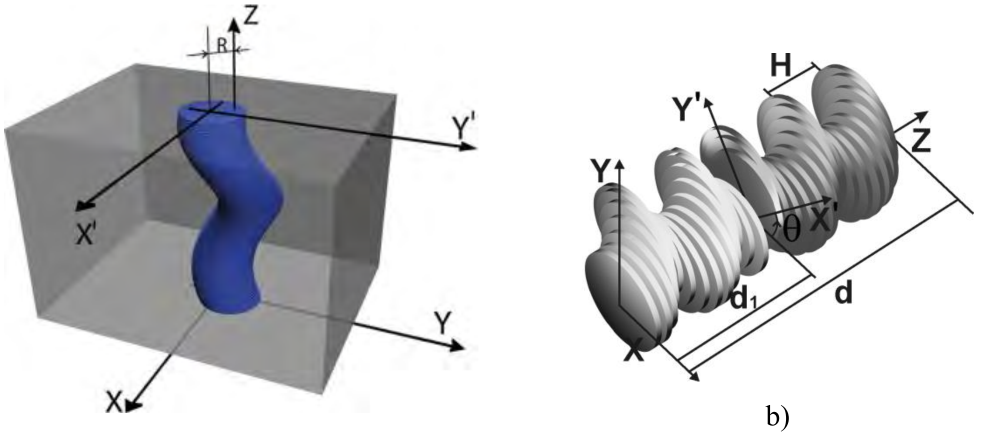
Amazing progress in data transfer by fiber-optic systems in past years [1, 3] suggests that future telecommunication systems would use light as information carrier. Indeed, data transfer rate in optical diapason ($\sim 10^{14}$ Hz) is higher by several orders than the one in the diapason, inherent for traditional wire communication lines ($\sim 10^{10}$ Hz). Moreover, another possibility to increase the data transfer rate exists for fiber-optic systems concerned with application of optical vortices (OVs) [4]. Indeed, in [5] it has been shown that a helical core fiber can maintain undamped propagation of OV with $\pm 1$ topological charge. According to [6, 7], OVs with different topological charges can be used for information encoding.

It is natural to suppose that more reliable methods of OV generation [8-14] for fiber-optic systems will be based on the use of optical fibers as generation and transporting elements. In the light of success in OV generation by microstructured helical core fiber (HCF) [14] it is desirable to know how diverse defects, which are inevitably present in real systems, will affect the generation processes. The aim of this paper is to show how the twist defect in a layered HCF with one-fold rotational symmetry affects the generation of 1-charged OV from the fundamental mode.

## 1. MODEL AND MODES OF LAYERED HELICAL CORE FIBER

The layered HCF with one-fold rotational symmetry is a set of dielectric layers, which centers lie on a spiral line with radius $R$ (Fig.1a). In the center's area the refractive index has a maximal value $n_{co}$. The linear size of this area is defined by $r_0 \ll R$. Another region of a layer has refractive index value equal to $n_{cl} < n_{co}$.

Let us now consider the HCF with a twist defect, which is placed at a distance $d_1$ from the input end of the fiber (Fig. 1 b). The twist defect appears where a fiber is transversely cut and the second part of the fiber is rotated around the mutual axis by an angle $\theta$.



a)

b)

Fig. 1. a) The model of layered helical core fiber, where $R$ – offset, $(X,Y,Z)$ and $(X',Y',Z')$ – laboratory and local coordinate systems; b) helical core fiber with a twist defect: $d_1$ – the distance from it to the input end of the fiber, $d$ – the length of a whole fiber, $\theta$ characterizes the degree of mutual twist of fiber's parts, $H$ – the pitch of spiral line.

As is known, if the lattice vector $q = 2\pi / H$ of the HCF satisfies the resonance condition $q \approx q_0 \equiv \tilde{\beta}_0 - \tilde{\beta}_1$, where $\tilde{\beta}_0, \tilde{\beta}_1$ are the scalar propagation constants of the $HE_{11}$ and $LP_{11}$ modes, intensive hybridization of these modes takes place. The structure of coupled modes near the resonance is:

$$|\Psi_1\rangle = \left\{ c_1 |1,0\rangle e^{i(\tilde{\beta}_0 + 0.5\varepsilon)z} + c_2 |1,1\rangle e^{i(\tilde{\beta}_1 - 0.5\varepsilon)z} \right\} e^{iz\gamma},$$

$$|\Psi_2\rangle = \left\{ -c_2 |1,0\rangle e^{i(\tilde{\beta}_0 + 0.5\varepsilon)z} + c_1 |1,1\rangle e^{i(\tilde{\beta}_1 - 0.5\varepsilon)z} \right\} e^{-iz\gamma}, \qquad (1)$$

where $c_1 = \cos\chi$, $c_2 = \sin\chi$, $\tan\chi = Q / \left( \sqrt{\varepsilon^2 + Q^2} - \varepsilon \right)$, $\gamma = 0.5\sqrt{\varepsilon^2 + Q^2}$, $\varepsilon = q - q_0$, $Q$ – coupling integral [12]. In the basic of linear polarizations $|\sigma, l\rangle = F_l(r) \begin{pmatrix} 1 \\ \sigma i \end{pmatrix} e^{il\varphi}$, $F_l$ is the standard radial function. Expressions (1) are written in cylindrical-polar coordinates $(r, \varphi, z)$. Expressions for modes in the second part of the fiber can be obtained by making the substitutions: $|\sigma, l\rangle \to |\sigma, l\rangle e^{-i(l+\sigma)\theta}$ and $z \to z - d_1$.

## 2. INFLUENCE OF THE TWIST DEFECT ON GENERATION OF OPTICAL VORTEX FROM THE FUNDAMENTAL MODE

Let us consider how the defect's location affects the evolution of the fundamental mode $|1,0\rangle$, which is known to converse into the optical vortex $|1,1\rangle$ in the HCF with the length $d = S_k \equiv \pi / Q(1+2k)$, $k = 0,1,2...$ Decomposing the fundamental mode $|1,0\rangle$ in modes (1) and using matching conditions on the boundaries of the fibers one can obtain:

$$\begin{gathered}\Phi_{II}(d) = \left(P_1 c_1 e^{i\gamma(d-d_1)} - P_2 c_2 e^{i\gamma(d-d_1)}\right) e^{i\left(\tilde{\beta}_0+0.5\varepsilon\right)(d-d_1)} |1,0\rangle + \\ \left(P_1 c_2 e^{i\gamma(d-d_1)} - P_2 c_1 e^{i\gamma(d-d_1)}\right) e^{i\left(\tilde{\beta}_1-0.5\varepsilon\right)(d-d_1)-i\theta} |1,1\rangle \equiv A_0 |1,0\rangle + A_1 |1,1\rangle\end{gathered}, \qquad (2)$$

where $P_{1,2} = \pm c_{1,2} e^{i\left(\tilde{\beta}_0+0.5\varepsilon\right)d_1} \left(c_1^2 e^{i\gamma d_1} + c_2^2 e^{-i\gamma d_1}\right) + 2ic_{2,1} e^{i\left(\tilde{\beta}_1-0.5\varepsilon\right)d_1+i\theta} c_1 c_2 \sin\gamma d_1$. $|A_i|^2$ defines the power of the corresponding field's components at the output end of the fiber.

Consider the case where $\lambda = \lambda_0 = 632.8$ nm $(\varepsilon = 0)$. Then the powers of the fundamental mode and the OV can be written as:

$$|A_{0,1}|^2 = \frac{1}{2} \mp \frac{1}{2}\left[-\cos Qd_1 \cos Q(d-d_1) + \sin Qd_1 \sin Q(d-d_1) \cos(q_0 d_1 - \theta)\right]. \qquad (3)$$

Obviously, one has $|A_0|^2 + |A_1|^2 = 1$. If the length of the fiber $d = S_0$ and $\theta = q_0 d_1$ (defect is absent) then the incoming fundamental mode entirely converts into the OV $|1,1\rangle$ that coincides with the well known results [12].

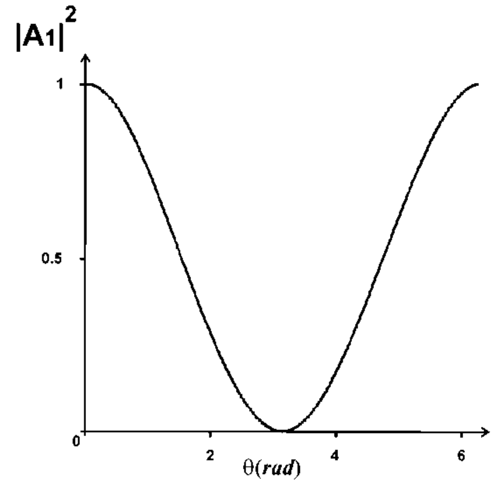
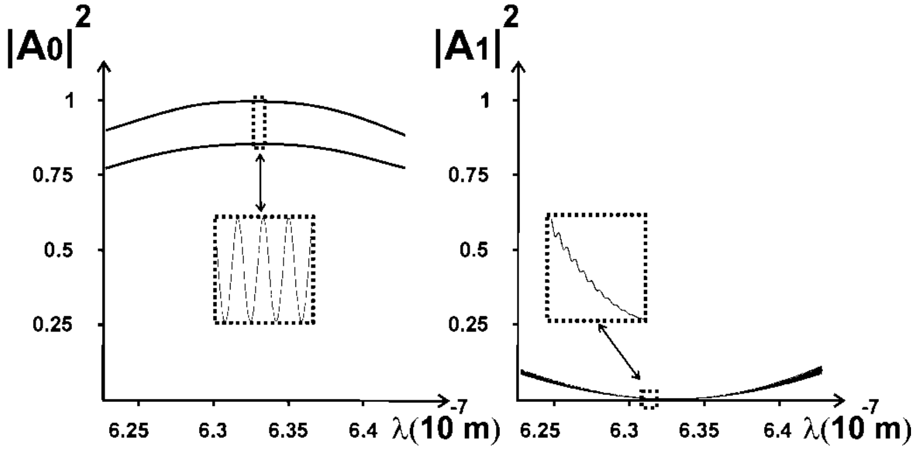


Fig. 2. Dependence of the transformation coefficient $|A_1|^2$ on $\theta$ at $\varepsilon = 0$. The fiber parameters: $n_{co} = 1.5$, $\Delta = 0.01$, $R / r_0 = 0.05$, $r_0 = 10\lambda_0$, $\lambda_0 = 632.8$ *nm*, $q = 6444.24$ m$^{-1}$, $d_1 = 0.5S_0, d = S_0 = 5$ mm.

From (3) one can obtain that the influence of the defect is negligibly small if the defect is located near one of fiber's ends and $d=S_0$. Indeed, at $d-d_1 \to 0$ or $d-d_1 \to \pi / Q(1+2k)$ the power of the output OV $|A_1|^2 \to 1$. For example, the dependence of the OV's output power on $\theta$ is shown in Fig. 2.

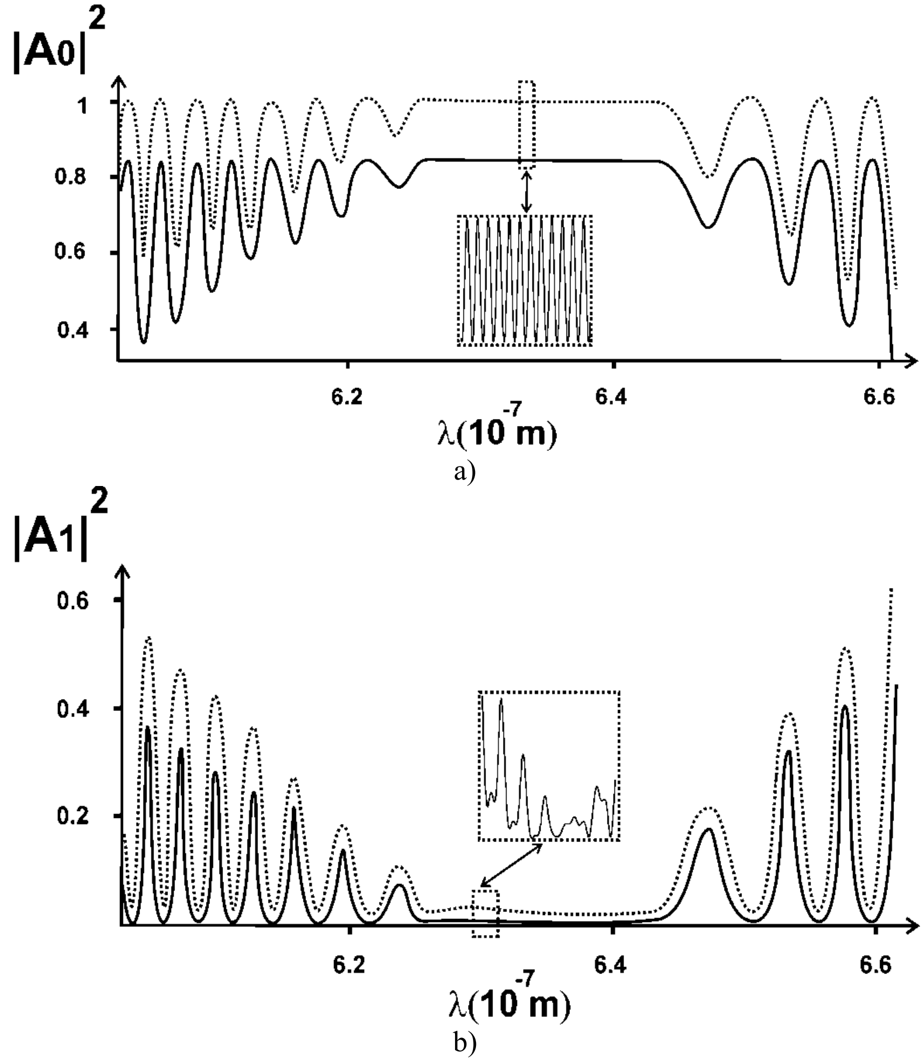
In the case where $\varepsilon \neq 0$ one can obtain similar expressions for $|A_i|^2$. In Fig. 3 the curves for transformation coefficient are shown at $d=\pi / Q$ and $\varepsilon \neq 0$ obtained with the help of numerical calculations.



a) b)

Fig. 3. Dependence of the transformation coefficients $|A_i|^2$ at $\theta=\pi+q_0 S_0 / 2$. The fiber parameters: $n_{co}=1.5$, $\Delta=0.01$, $R / r_0=0.05$, $r_0=10 \lambda_0$, $\lambda_0=632.8\ nm$, $q=6444.24\ \mathrm{m}^{-1}$, $d_1=0.5 S_0$, $d=S_0=5$ mm. Solid lines correspond to the envelopes for the transformation coefficient $|A_0|^2$. The fine structure of the transformation coefficients is shown on the insets.

As is seen from Fig. 3, at $\varepsilon \neq 0$ and $\theta=\pi+q_0 S_0 / 2$ part of energy of the incoming fundamental mode transfers into the OV $|1,1\rangle$. It is connected with the dependence of the conversion length $S_k$ on $\lambda$: $S_k(\lambda)=\pi(1+2k) / \sqrt{\varepsilon^2+Q^2}$. The last expression makes it evident that the fundamental mode with $\lambda \neq \lambda_0$ needs larger distance for conversion into the OV $|1,1\rangle$. From Fig. 4 it can be seen that at significant increase of the length $(d=S_{100})$ there are areas where appreciable part of energy is stored in the OV $|1,1\rangle$ (Fig. 4 b). Nevertheless, at $\varepsilon \approx 0$ the fundamental mode almost completely passes through the fiber (Fig. 4 a). It should be noted that these curves have a fine structure. It can be explained by the action of the whole fiber. Indeed, in (2) at the right boundary of the fiber there are factors $e^{i\tilde{\beta}_0(\lambda)(d-d_1)}$. Since $\tilde{\beta}_0(\lambda_0)d \sim 10^3 \div 10^4$ even small change of the wavelength $\lambda$ leads to fast oscillations of these factors and hence of $|A_i|^2$. Large scale oscillations can be explained by the presence of the factors $e^{i\gamma(\lambda)d}$: $\gamma(\lambda_0)S_0 \sim 1$.



a)

b)

Fig. 4. Dependence of the transformation coefficients $|A_i|^2$ at $\theta = \pi + q_0 S_{100}/2$. The fiber parameters: $n_{co} = 1.5$, $\Delta = 0.01$, $R/r_0 = 0.05$, $r_0 = 10\lambda_0$, $\lambda_0 = 632.8\ nm$, $q = 6444.24$ m$^{-1}$, $d_1 = 0.5S_{100}$, $d = S_{100} = 1.0178$ m. Solid and dot lines are envelopes for the transformation coefficients. The fine structure of the transformation coefficients is shown on the insets.

## CONCLUSION

In conclusion one can say that the twist defect can appreciably affect the optical vortex generation from the fundamental mode in a layered helical core fiber. Influence of twist defect is maximal where it is located right in the middle of the fiber. This leads to complete suppression optical vortex generation at resonance wavelength. If the defect is located near one of fiber's ends and the fiber's length is equal to $S_0$ the influence of the defect is negligibly small.

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**Лапін Б. П. Вплив дефекту скрутки в шаруватому волокні з спіральною серцевиною на генерацію оптичного вихору з одиничним зарядом / Б. П. Лапін** // Вчені записки Таврійського національного університету імені В. І. Вернадського. Серія : Фізико-математичні науки. – 2013. – Т. 26 (65), № 2. – С. 31-37.

Описано, як дефект скрутки у шаруватому волокні з спіральною серцевиною впливає на генерацію оптичного вихору з одиничним топологічним зарядом з фундаментальної моди. Вплив дефекту скрутки максимальний, коли він знаходиться точно посередині волокна, і призводить до повного пригнічення генерації оптичного вихору. Крім того, встановлено, що вплив дефекту скрутки на генерацію оптичного вихору незначний, коли дефект розташований поблизу одного з кінців волокна, а довжина волокна дорівнює нульової довжині конверсії.

***Ключові слова:*** оптичний вихор, волокно з спіральної серцевиною, оптичне волокно.

**Лапин Б. П. Влияние дефекта скрутки в слоистом волокне с геликоидальной сердцевиной на генерацию оптического вихря с единичным зарядом / Б. П. Лапин** // Ученые записки Таврического национального университета имени В. И. Вернадского. Серия : Физико-математические науки. – 2013. – Т. 26 (65), № 2. – С. 31-37.

Описано, как дефект скрутки в слоистом волокне с геликоидальной сердцевиной влияет на генерацию оптического вихря с единичным топологическим зарядом из фундаментальной моды. Влияние дефекта скрутки максимально, когда он находится точно посередине волокна, и приводит к полному подавлению генерации оптического вихря. Кроме того, было установлено, что влияние дефекта скрутки на генерацию оптического вихря пренебрежимо мало, когда дефект расположен вблизи одного из концов волокна, а длина волокна равна нулевой длине конверсии.

***Ключевые слова***: оптический вихрь, волокно с геликоидальной сердцевиной, оптическое волокно.

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