Localized topological states in Bragg multihelicoidal fibers with a twist defect in the presence of a spacer

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Abstract. We have studied the influence of a spacer in a multihelicoidal Bragg fiber with a twist defect on the emerging of localized topological states. We have shown that if such a fiber is excited with a Gaussian beam this leads to the appearance of a defect-localized mode, whose topological charge coincides with the order of rotational symmetry of the fiber’s refractive index distribution. The influence of the spacer on this mode is studied.

1. Introduction
As has been established periodic dielectric structures can nestle the localized states near areas of their imperfections [1]. Inducing imperfections in photonic band-gap structures enables a number of useful applications [2-7]. For band-gap photonic structures the presence of a single defect results in the emergence of a localized defect mode, the spectral line of which is positioned within the forbidden spectral band [8].

The way of embedding a single defect into a periodic dielectric structure depends on its symmetry. If the structure possesses a rotational degree of freedom then one can insert the defect into it by twisting the first part of the structure with respect to the second. It was demonstrated that localized states exist near twist defects in cholesteric polymer films in the optical range. However, it was shown only for the waves with no wavefront dislocations [9,10]. To the best of our knowledge, the first study concerning the case of the waves with wavefront dislocations or optical vortices (OVs) [11] was carried out by Lobanov et al. [12]. It has been shown that evolution of the incident OV with unit topological charge within disordered array is accompanied by flipping of the topological charge between the values $\pm 1$. As opposed to this study, the influence of a single defect on the evolution of the input beam was considered in the multihelicoidal fibers (MHF), which present one-dimensional photonic band-gap structures, by Alexeyev et al. It has been demonstrated that introducing the twist defect into the Bragg MHF results in the localization of OVs, whose topological charges coincide with the order of the rotational symmetry of the MHF [13]. The intensity of the localized fields in the vicinity of the twist defect turns out to be much greater than the one of the incident beam. Subsequently, it has been shown that combining the twist defect with the pitch jump allows one to control the intensity of the localized states in a wide range [14].

In this paper we make a further step by considering the MHF with the twist defect in the presence of a spacer. We show that exciting such defected fiber with the circularly polarized (CP) Gaussian beam (GB) results in the appearance of defect-nested localized states, which can be controlled by adjusting the thickness of the spacer.

2. The model of the multihelicoidal fiber
The refractive index distribution of a MHF with a twist defect and the spacer is given by [13-19]:
localized fields in the defected multihelicoidal fiber

To study the evolution of the input field one has to decompose it in the modes of a Bragg MHF [14] and ideal fiber modes in the corresponding parts of the system with an appropriate matching the fields and their derivatives with respect to \( z \) on the boundaries. This allows one to obtain the system in unknown decomposition coefficients, which can be used while restoring the field’s expressions within the defected MHF. Further we will focus our attention on the case where the fiber is excited with the CP GB, which may be approximated near the input end by the fundamental mode \( |1,0\rangle \). In the following we set in numerical simulations \( l = 4 \) and \( \theta = \pi / 4 \).

As numerical simulations show, there are three localized states within the defected MHF: \( |1,0\rangle \) and \( |l,\pm l\rangle \), where \( |l,\pm l\rangle = F_l(r) \exp(\imath l \varphi) \cdot \text{col}(1,l) \) and \( F_l(r) \) satisfies the standard equation. Figure 2a shows relative averaged energy density distribution within the system in study at the wavelength \( \lambda = 632.8 \text{ nm} \). The averaging is carried out over the fast spatial oscillations caused by interference effects. The intensity of each of the modes in the MHF parts falls down exponentially with the distance from the spacer. At the same time, the averaged energy density distribution within the spacer remains constant. As is seen from Figure 2b, the energy of the localized fields stored within the MHF essentially depends on the length of the spacer and is very sensitive to its variations even on the wavelength scale. As the length of the MHF part grows the effect of the field’s localization decreases (Figure 3a). The energy of the localized modes also decreases (Figure 3b). Such behavior of the system is connected with the fact that the influence of the single defect on the system’s ability to localize fields lessens as the total length of the MHF part grows.
Figure 2. a) Logarithm of the relative energy density distribution within the fiber averaged over fast spatial oscillations vs position $z$ within the fiber, the spacer thickness $d = 3000 \lambda_{\text{He-Ne}}$; b) logarithm of the relative stored in fiber energy of the localized fields vs the spacer’s thickness $\delta d$. The type of the field is indicated near the curve, incident beam is $|1,0\rangle$ at the wavelength $\lambda = 632.8 \text{ nm}$. Fiber parameters: $q = 7.436 \cdot 10^4 \text{ m}^{-1}$, $n_{\infty} = 1.5$, $\Delta = 5 \cdot 10^{-3}$, $\delta = 0.05$, $d_i = 1 \text{ cm}$. Here and throughout energy density $P$ and spectral energy density $W$ are normalized to energy density $P_0$ and spectral energy density $W_0$ of the incident GB, respectively.

The stored in the fiber energy also depends on the spacer’s thickness and tends to zero as it grows (Figure 4). As is seen from Figure 4 the energy reaches the maximum value at the certain spacer’s thickness.

Figure 3. a) Logarithm of the relative energy density distribution within the fiber averaged over fast spatial oscillations vs position $z$ within the fiber, the spacer thickness $\delta d = 3000 \lambda_{\text{He-Ne}}$; b) stored in the fiber energy of the localized fields vs the spacer’s thickness $\delta d$. The type of the field is indicated near the curve, incident beam is $|1,0\rangle$ at the wavelength $\lambda = 632.8 \text{ nm}$. Fiber parameters are the same as in Figure 2 except $d_i = 1.5 \text{ cm}$. 
Figure 4. Logarithm of the stored in the fiber energy of the localized fields vs spacer’s thickness $\delta d$. The type of the field is indicated near the curve, incident beam is $|1,0\rangle$. Fiber parameters are the same as for Figure 2.

4. Conclusion
In conclusion, we have studied influence of the spacer on the emerging of the localized mode. We have shown that the presence of the spacer results in the extension of the localization’s zone, but as its thickness grows the effect of localization vanishes.

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