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Dual-core chiral planar waveguide-based compact and efficient dispersion compensator

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ABSTRACT

The paper is devoted to the design of dispersion compensator comprised of dual-core planar chiral waveguide having different refractive indices, and cladded with homogeneous dielectric mediums. It has been found that the supermodes play vital role in tuning the group velocity dispersion (GVD) with the aid of chirality parameters, which is evident from the achieved giant GVD with narrow bandwidth. Apart from the material parameters, the effect of core spacing on the features of GVD is also investigated. It is expected that such dispersion compensators would be trendy and greatly useful in communication systems.

1. Introduction

Negatively refractive mediums having the real parts of both the constitutive parameters, i.e. the permittivity and the permeability negative [1,2], can be achieved with the aid of suitable arrangements of unit cells in either periodical or random fashions [3]. Since the last decade, many researchers belonging to the fields of optics, photonics and materials science have been attracted by these materials due to their unique features such as the usefulness in devising negative refractive index, invisible cloaks, perfect lenses, and subwavelength imaging [4–8]. Within the context, V.G. Veselago and his co-worker presented interesting phenomena of the propagation of light in metamaterials [9–12]. The use of chiral metamaterials constitutes one of the ways for the fabrication of such materials at optical frequencies, which brings forth revolutionary breakthrough in optical storage industries [13–15]. Within the context, plenty of research articles have been reported in the literature for the purpose of theoretical realization of negatively refracting mediums through the use of chirality, particularly the design of perfect lens by implementing chiral slab [16–18.] Further, at certain resonance frequency, chiral metamaterials can be tailored to chiral nihility metamaterials [19–21], which exhibit fascinating behavior in the form of backward wave propagation [22].

In communication systems, transmission of bit rates for data transfer gets limited by the effects due to dispersion caused by materials, waveguide geometries, and also, optical amplification. Metamaterial-based communication devices also suffer from such problems due to their resonance dependency, thereby leading to signal distortion. Within the context, many theoretical and experimental approaches have been developed to reduce such effect due to distortion [23–27].

One of the notable group velocity dispersion (GVD) compensating devices would be based on coupled waveguide structure, where the supermodes are excited at certain frequency to generate a giant GVD that leads to pulse compression. Within the context, Peschel et al. [28] proposed the design that implements two dissimilar waveguides using Si/SiON/SiO_2 sandwiched between two mode converters, which excite the supermodes. While Ref. [29] reports the use of similar approach using the InGaAsP/InP coupled waveguides, the supermodes are, however, excited by the transverse electric TE_0 (in waveguide 1) and the transverse electric TE_2 (in waveguide 2) modes, instead of mode converters, as used by Peschel et al. in [28]. Further, the inclusion of clad in the design of coupled waveguide leads to the formation of giant GVD [30]. Such an approach yields very low absorption and insertion losses, and has been extensively used in fiber-based networks, sensors and ultrashort-pulse semiconductor lasers [31,32].

Compact and efficient devices used in communication systems are required to exhibit tunable GVD. The use of nihility mediums in tailoring the GVD has been reported before [33]. However, the curiosity remains if the tailoring of GVD can also be achieved by the use of chiral mediums. If at all possible, how the parametric values are then to be tailored? With this viewpoint, the present paper focuses on achieving the desired GVD with the utilization of chiral materials in dual-core planar waveguide structure, where the supermodes are excited by the coupling of two particular modes propagating in individual guide, and result into an effective giant GVD. Numerical results yield that the core spacing and the

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chirality parameter of medium present in core-2, along with clad refractive index (RI), would play key role in achieving a high GVD. In line with this, more appropriate result is observed with the adjustment of core-1 chirality. In optical communication systems, such kind of design of dispersion compensation system would improve the power handling capacity for the device, and also, would be of great potential in laser-based technologies.

2. Analytical treatment

We consider a dual-core planar waveguide structure comprised of different kinds of chiral mediums (with the chirality parameters as κ_1 and κ_2) inside, and separated by crown glass – a homogeneous dielectric medium that is cladded with dielectric silica material. All these layers are developed on a substrate, and the free-space is present next to the clad layer, as illustrated in Fig. 1. The RI values of substrate and the spacer between the two cores are assumed as the same, and is represented by n_s along with the property $n_{cl} < n_s$; n_{cl} being the RI of the clad section. Different layers are extended along the x-direction, and the values of spacing between them are as shown in Fig. 1.

The constitutive relations for chiral medium in the core region can be written as

$$\boldsymbol{D}_p = \varepsilon_p \boldsymbol{E}_p - j\kappa_p \sqrt{\varepsilon_0\mu_0}\,\boldsymbol{H}_p \tag{1a}$$

$$\boldsymbol{B}_p = \mu_p \boldsymbol{H}_p + j\kappa_p \sqrt{\varepsilon_0\mu_0}\,\boldsymbol{E}_p \tag{1b}$$

where $p(=2,4)$ in the subscript represents the situations in core-1 and core-2, ε and μ are the permittivity and the permeability, respectively, and the quantity κ is a normalized and dimensionless chirality parameter, which shows the handedness of the medium. After substituting the above constitutive relations in the source-free Maxwell's equations, we obtain the following coupled-wave equations:

$$\nabla_t^2 \boldsymbol{E}_p + \left[k_p^2\left(1+\kappa_p^2\right) - \beta^2\right]\boldsymbol{E}_p - 2jk_p^2\kappa_p\eta_p\boldsymbol{H}_p = 0 \tag{2a}$$

$$\nabla_t^2 \boldsymbol{H}_p + \left[k_p^2\left(1+\kappa_p^2\right) - \beta^2\right]\boldsymbol{H}_p + \frac{2jk_p^2\kappa_p}{\eta_p}\boldsymbol{E}_p = 0 \tag{2b}$$

with $k_p = \omega\sqrt{\varepsilon_p\mu_p}$. For $\kappa_p=0$, the above equations simply reduce to the Helmholtz's wave equations. Now, the TE and the TM modes do not exist in chiral mediums; only the hybrid modes are supported. Hence, the solutions to the axial E- and the H-field components can be determined by solving the above coupled-wave equations, and are assumed to be of the form as

$$E_{pz} = A_{p+}e^{jk_{p+}(x-d_q)} + B_{p+}e^{-jk_{p+}(x-d_q)} + A_{p-}e^{jk_{p-}(x-d_q)} + B_{p-}e^{-jk_{p-}(x-d_q)} \tag{3a}$$

$$H_{pz} = \frac{j}{\eta_p}\Big[A_{p+}e^{jk_{p+}(x-d_q)} + B_{p+}e^{-jk_{p+}(x-d_q)} - A_{p-}e^{jk_{p-}(x-d_q)} - B_{p-}e^{-jk_{p-}(x-d_q)}\Big] \tag{3b}$$

In these equations, A_p and B_p are the unknown constants with the positive and the negative signs in the subscript as determining the right-handed and the left-handed waves, respectively, propagating through the medium; the resultant wave will be the superposition of the two. Also, the quantity d_q is taken as – for $p=2$, $d_q=d_1$ (the interface between the substrate and the core-1) and for $p=4$, $d_q=d_3$ (the interface between the dielectric spacing and the core-2).

Now, the transverse **E**- and the **H**-field components in each of the cores can be obtained by using Maxwell's equations, and would be given in the matrix form as

$$\begin{pmatrix} E_x \\ E_y \\ H_x \\ H_y \end{pmatrix} = \begin{pmatrix} -j\dfrac{\beta}{\sigma_{p+}^2} & \dfrac{k_{p+}}{\sigma_{p+}^2} & -j\dfrac{\beta}{\sigma_{p-}^2} & -\dfrac{k_{p-}}{\sigma_{p-}^2} \\ -\dfrac{k_{p+}}{\sigma_{p+}^2} & -j\dfrac{\beta}{\sigma_{p+}^2} & \dfrac{k_{p-}}{\sigma_{p-}^2} & -j\dfrac{\beta}{\sigma_{p-}^2} \\ \dfrac{\beta}{\eta_p\sigma_{p+}^2} & j\dfrac{k_{p+}}{\eta_p\sigma_{p+}^2} & -\dfrac{\beta}{\eta_p\sigma_{p-}^2} & j\dfrac{k_{p-}}{\eta_p\sigma_{p-}^2} \\ -j\dfrac{k_{p+}}{\eta_p\sigma_{p+}^2} & \dfrac{\beta}{\eta_p\sigma_{p+}^2} & -j\dfrac{k_{p-}}{\eta_p\sigma_{p-}^2} & -\dfrac{\beta}{\eta_p\sigma_{p-}^2} \end{pmatrix} \begin{pmatrix} \dfrac{\partial}{\partial x}E_{z+} \\ \dfrac{\partial}{\partial y}E_{z+} \\ \dfrac{\partial}{\partial x}E_{z-} \\ \dfrac{\partial}{\partial y}E_{z-} \end{pmatrix} \tag{4}$$

where $\sigma_{\pm}=(k_{p\pm}^2-\beta^2)^{1/2}$, $k_{p\pm}=k_0n_p(1\pm\kappa_p)$ and $\eta_p=\sqrt{\mu_p/\varepsilon_p}$. Similarly, we can write the axial and the transverse E- and the H-field components in the remaining layers of the waveguide structure [33].

We use the transfer matrix method [34] to analyze the waveguide structure, wherein we apply the boundary conditions at every interface (present in the structure) individually. By implementing this process, we determine the unknown constants. Further, by applying the boundary conditions [33] in the outer most layers (the substrate and the free-space) of the structure, it can be shown that the dispersion relation will finally assume the form as

$$\vartheta e^{jk_{5x}(d_5-d_4)} + \psi e^{-jk_{5x}(d_5-d_4)} + \chi e^{jk_{5x}(d_5-d_4)} + \tau e^{-jk_{5x}(d_5-d_4)} + j\left(\frac{k_{6x}\varepsilon_5}{k_{5x}\varepsilon_6}\right)\Big[\vartheta e^{jk_{5x}(d_5-d_4)} - \psi e^{-jk_{5x}(d_5-d_4)} - \chi e^{jk_{5x}(d_5-d_4)} - \tau e^{-jk_{5x}(d_5-d_4)}\Big] = 0 \tag{5}$$

The meanings of all the symbols used in Eq. (5) are extensively mentioned in the Appendix.

The coupling of particular modes (in individual guide) for the generation of supermodes and the excitation of the GVD can be determined [28]; indeed, the modal propagation constants (for particular mode) remain of great importance in this context.

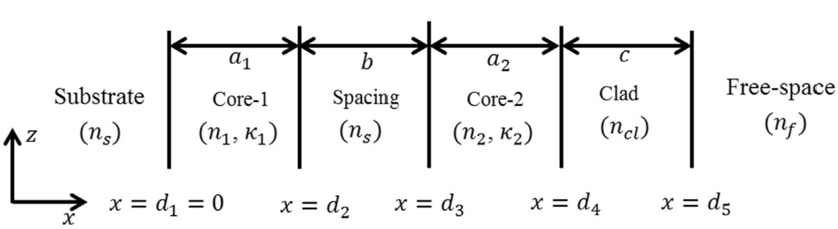

Fig. 1. Layered structure of dual-core planar waveguide.