Optics Communications 365 (2016) 120–124

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Invited Paper

An approach of waveguide mode selection based on the thin-film spatial filters

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ARTICLE INFO

Article history:
Received 2 August 2015
Received in revised form
4 November 2015
Accepted 5 December 2015
Available online 14 December 2015

PACS:
42.82-m
42.82.Et
42.79.Gn
42.79.Ci

Keywords:
Waveguide
Mode selection
Spatial filter

ABSTRACT

A novel approach is presented for waveguide mode selection by using thin-film spatial filters embedded in multimode waveguides. The waveguide modes are allowed to pass through the spatial filters if and when their mode angles fall within the angle-domain bandwidth of the filters. Consequently the waveguide modes are selectable with varied angle-domain bandwidth of the spatial filters. This approach is relatively simple, cost-effective and features good suppression effect of high-order modes, and is suitable for high-power laser systems.

1. Introduction

The waveguide mode selection has attracted considerable attention in the optoelectronic field, especially in respect of high-power laser system [1–17]. A perfect waveguide structure for high-power applications should be one that has a large core and supports only a single mode for the purpose of reducing nonlinear optical effects and avoiding mode competition and intermodal dispersion. In fact, the high-order modes are stimulated inevitably with the increase of the waveguide core diameter, resulting in poor quality of the output beam. For large core single-mode operation, various approaches have been proposed including those based on photonic crystal fibers [1–3], bend waveguide [4–6], tapered optical fibers [7–9], leaky optical waveguide [10,11], gain guided fibers [12–14] and helical fibers [15–17]. Among the said approaches, the one based on the photonic crystal fibers possesses excellent suppression effect of high-order modes, but the cost is high due to the complicated production process of photonic crystal fibers. Although the bend waveguide approach is relatively simple, the suppression effect of high-order modes is all the same poor for larger core. Moreover, all of the other approaches necessitate a special, high-cost production process. Therefore, new approaches of mode selection were highly sought after over the past two decades.

Recently, some thin-film spatial filters have been performed, and the known theoretical and experimental implementations of the filters involve those based on anisotropic media [18], multilayer stacks with a prism [19], resonant grating system [20], interference patterns [21], metallic grids over a ground plane [22] and photonic crystals [24–26,23,27–29]. A conventional spatial filter is implemented by the use of a telescope consisting of two focusing lenses in a confocal arrangement and an appropriate pinhole in the focus plane. The conventional focus-type spatial filter has been widely used to improve the beam quality in high-power laser system. Unlike the conventional spatial filter, the thin-film ones are compact and realizes plug-and-play, for example. Also, these spatial filters are more cost-effective because they do not require high performance lens and a perfect vacuum condition as required for conventional ones owing to high power density of the focus in the relatively large laser system. The applications of beam smoothing for the thin-film spatial filters have been discovered [23,32].

In this paper, we propose a novel approach of waveguide mode selection by embedding the thin-film spatial filters in the multimode waveguide. The approach can suppress the high-order modes of waveguide, thereby improving the quality of laser beam. In addition, it is relatively simple, cost-effective and so forth.

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http://dx.doi.org/10.1016/j.optcom.2015.12.009

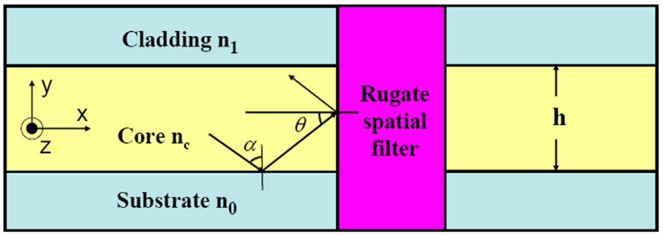

Fig. 1. The schematic of waveguide mode selection based on the rugate spatial filters in the conventional dielectric slab waveguide. n_c, n_0 and n_1 indicate the refraction indexes of the core, substrate and cladding, respectively. h denotes the thickness of the core. α and θ are the incidence angle of plane wave on the waveguide interface and the rugate spatial filter, respectively.

2. Structure model and theory

To demonstrate this approach of waveguide mode selection, we take an example of embedding the rugate spatial filters in the conventional dielectric slab waveguide as shown in Fig. 1. n_c, n_0 and n_1 indicate the refraction indexes of the core, substrate and cladding of the slab waveguide, respectively. h denotes the thickness of the core. Since either substrate or cladding is thicker than the core, they can be regarded as infinite medium in theory analysis. The thickness of the waveguide can also be used as infinite along the z direction, so light is only constrained in the y direction. We assume that a plane wave propagates in the dielectric slab waveguide, with the incidence angle on the waveguide interface being represented by α. The plane wave must be injected from the waveguide at an angle θ into the rugate spatial filter in the $+x$ direction. The relationship between the two angles is $\alpha = \frac{\pi}{2} - \theta$. Incidentally, rugate structure is a kind of optical thin film with graded refractive-index profiles, and it offer unique advantages including low internal stress, suppression of sidelobes, and continuous index matching for broadband anti-reflection coatings [30,31]. The spatial filter based on the rugate structure is a thin-film one, and has excellent transmittance properties of both an almost ideal flat bandpass and a rather steep switching between pass- and stop-bands [32].

According to the waveguide theory [33,34], the eigen-equation of the dielectric slab waveguide is as follows:

$$2k_0 n_c h \sin\theta - \varphi_1 - \varphi_2 = 2m\pi, \tag{1}$$

where k_0 is the vacuum wavenumber, φ_1 and φ_2 are the phase shifts on total reflection at the interfaces of core-cladding and core-substrate, respectively. m is an integer $(m = 0, 1, 2, 3, \ldots)$ which refers to the mth confined TE (or TM) mode. The phase shifts φ_1 and φ_2 for TE or TM waves can be expressed conveniently by using the following equations:

$$\tan\frac{\varphi_1}{2} = \begin{cases} \dfrac{\sqrt{\cos^2\theta - \left(\dfrac{n_1}{n_c}\right)^2}}{\sin\theta}, & \text{(TE)} \\[2ex] \left(\dfrac{n_c}{n_1}\right)^2 \dfrac{\sqrt{\cos^2\theta - \left(\dfrac{n_1}{n_c}\right)^2}}{\sin\theta}, & \text{(TM)} \end{cases} \tag{2}$$

$$\tan\frac{\varphi_2}{2} = \begin{cases} \dfrac{\sqrt{\cos^2\theta - \left(\dfrac{n_0}{n_c}\right)^2}}{\sin\theta}, & \text{(TE)} \\[2ex] \left(\dfrac{n_c}{n_0}\right)^2 \dfrac{\sqrt{\cos^2\theta - \left(\dfrac{n_0}{n_c}\right)^2}}{\sin\theta}. & \text{(TM)} \end{cases} \tag{3}$$

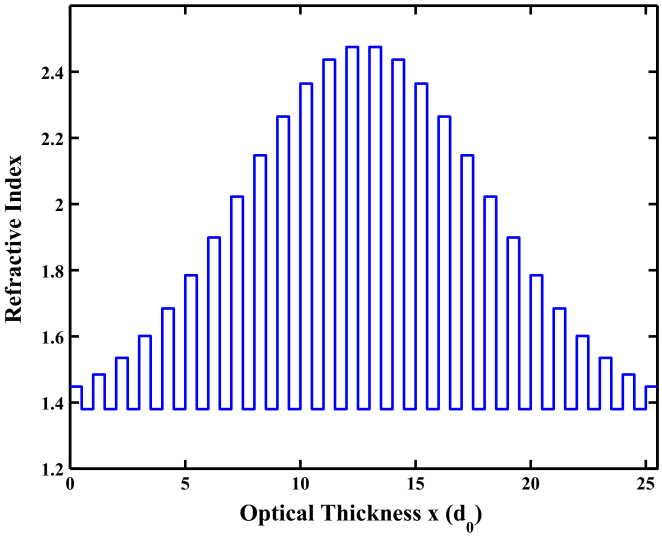

Fig. 2. The refractive-index profile of the rugate spatial filter. Structure parameters: each layer optical thickness d_0, the lowest index n_L=1.38, the peak-to-peak refractive-index variation n_p=1.2 and $\sigma = 4.4 \times 10^{-3}$.

From Eqs. (1)–(3), we can conclude that each value of m corresponds to a unique angle θ_m, and thus θ_m usually is called mode angle [35].

3. Numerical simulation and results

Firstly, we analyze the transmission properties of the conventional dielectric slab waveguide in Fig. 1. The core of the waveguide is made of LiF, which is surrounded by air. Their parameters are the following: n_c=1.38, $n_0 = n_1 = 1$, and $h = 1.65$ μm. According to the waveguide theory [33,34], this structure supports three TE modes (TE_0, TE_1, TE_2), and three TM modes (TM_0, TM_1, TM_2) as well. For TE modes, the fundamental mode, the first-order mode and the second-order mode (i.e. TE_m, $m = 0, 1, 2$) correspond to the mode angles θ_m=10.5°, 21.2° and 32.3°, respectively. Similarly, the TM_0, TM_1 and TM_2 modes correspond to the mode angles θ_m =11.4°, 23° and 34°.

Secondly, we design the rugate spatial filter on the basis of the theory as presented in Refs. [27,32]. The refractive-index profile of the rugate spatial filter is shown in Fig. 2, which can be written as [32]

$$n(x) = n_L + \frac{1}{2}n_p[1 + (-1)^q]e^{-\sigma q^2}. \tag{4}$$

Here n_L=1.38 (LiF) is the lowest index, n_p=1.2 is the peak-to-peak refractive-index variation, $\sigma = 4.4 \times 10^{-3}$ is a constant, q is the corresponding layer order for optical thickness x, and d_0 indicates each layer optical thickness. Usually, spatial filters have a very narrow frequency bandwidth or even monofrequency. From Ref. [32], we can infer that the angle-domain bandwidths of the spatial filters are sensitive to center wavelength, and the angle-domain bandwidth can be tuned by changing the center frequency. In this paper, we keep the center wavelength of the laser beam constant and adjust the angle-domain bandwidth of the spatial filters by changing the structure parameters to select different waveguide modes. In the ensuing discussion, we choose the center wavelength $\lambda = 1$ μm, and the transmission properties of these rugate spatial filters for different polarization using the transfer matrix method [27,36]. For the TE polarization, the angular dependence of transmittance of the rugate spatial filters is shown in Fig. 3 for each layer optical thicknesses $d_0 = 0.305$ μm, 0.329 μm and 0.386 μm, and their angle-domain bandwidths are $\Delta\theta = 13°$, 28° and 44°, respectively. Comparing the