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Design and Analysis Superprism Effects in 1D Photonics Crystal

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Abstract

Extraordinary angle-sensitive light propagation, which we call a superprismphenomenon,was demonstrated at optical wavelength in photonic crystals (PCs) with one dimensional (1D) periodic structure. This research shows that multilayer optical thin film stack can exhibit superprism effect due to their large abnormal dispersions. We investigated and simulated this effect numerically in a 1D non-periodic film structure.

Index Terms: Superprism, Photonic crystals, Group-propagation.

I. Introduction

Superprism effect is a special phenomenon existing in photonic crystals (PCs)[1,2]. Now-adays, many researches demonstrate that PCs possess anomalous dispersion and anisotropy properties near the bandgap, lead PCs achieve huge dispersion[3,4].

For one dimensional (1D) multilayer stacks, which own peculiar properties, can act as PCs, more and more people choose this structure to investigate superprism effect [5,6]. For Conventional 1D film stacks, we knowthe beam spatial separation caused by superprism effect is only proportional to the group delay accumulated throughout the structure, while it is independent of the wavelengths [7].

2. Theoretical Concept

Miniaturization of optical systems for spectroscopy and communications demands compact and cost effective components. Several groups have noted that a rapid change of the group-propagation angle with wavelength a superprism effect observed in one dimensional[8,9]. The change in the group propagation angle (Figure 1) can be used for wavelength multiplexing or demultiplexing by spatial beam shifting.

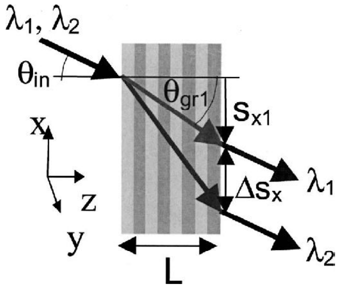

Figure 1: Superprism effect in a 1D photonic crystal [8, 9].

Ref. [10] showed that nonperiodic photonic nanostructures can also be designed for high and controllable spatial dispersion. Stack designs with a wavelength dependentpenetration depths, a change in the stored energy, or both were used. Where, the dispersion is related to a change in the stored energy in the stack with wavelength in all all-pass periodic and nonperiodic stacks, demonstrating the similarity between the superprism effect and spatial dispersion effects in nonperiodic photonic nanostructures. The result derived in two steps:

1. The spatial dispersion and temporal dispersion are approximately proportional.
2. The Tellegen's theorem relating the group delay to the stored energy in the structure.

So, the rapid change in effective group propagation angle withwavelength necessarily corresponds to a rapid change in stored energy with wavelength for all-pass periodic and nonperiodic 1D nanostructures [11].

An all-pass system is one that influences only signal phase, not amplitude. For steady state, the energy propagation direction is given by grouppropagation angleθ_{gr}, which is related to group velocities v_{gx}in the *x* and v_{gz}in the *z* directions by Eq. (1) for isotropic materials [6-8]:

$$\theta_{gr} = \tan^{-1}\left(\frac{v_{gx}}{v_{gz}}\right) \tag{1}$$

The group velocities are calculated as $v_{gx} = {}^{\partial\omega}/_{\partial\beta_k}$ and $v_{gz} = {}^{\partial\omega}/_{\partial K_\beta}$where ω is the frequency andβ and K are the wave vectors in the *x* and *z* directions, respectively.

For a plane wave incident at a particular angle on parallel, flat surfaces, β is constant and is fixed equal to the vacuum value of: $\beta = \omega \sin(\theta_{in}) / c$. θ_{in} is the propagation angle in vacuum, and *c* is the vacuum speed of light. For an infinite stack, $K(\omega, \beta)$can be calculated using Bloch theory. For finite stacks a transfer matrix method gives $K(\omega, \beta)$, v_{gx}, andv_{gz}, which are in this case effective quantities [6-13]. All angles are taken with respect to the *z* axis. Thus $\theta_{gr}$is 0° if the beam propagates along the z axis. In the case that K and β are given as functions of the frequency ω and the incidence angleθ, we can transform Eq. (1) into Eq. (2) by using a coordinate transformationand carefully calculating the partial derivatives:

$$\theta_{gr}\,(\theta,\omega) = \tan^{-1}\left[-\frac{\partial K(\theta,\omega)}{\partial\theta}\ /\ \frac{\partial\beta(\theta,\omega)}{\partial\theta}\right] \tag{2}$$

This group propagation angle is, of course, identical to the one obtained when we take the normal nin a wave vector diagram plotting contours of constant frequency [2,9].

$$n = -\frac{\partial K(\theta,\omega)}{\partial\theta}\,x + \frac{\partial\beta(\theta,\omega)}{\partial\theta}\,z \tag{3}$$

Finally, the exit position in reflection $s_x$along the surface of the dielectric stack in the x direction is given by Eq.4, whereθ_{gr} can be calculated with either Eq.(1)or Eq. (2):

$$s_x = 2L\ \tan(\theta_{gr}) = 2L\,({}^{v_{gx}}/_{v_{gz}}) \tag{4}$$

3. Designresults and Discussions

We designed 1D superprism structures based on the theory of thin film. The structure consists of alternating layers of high index material (n=2.34 at 550*nm*) and low index material (n=1.48 at 550*nm*) on quartz substrate (n=1.46), and the stack is arranged as:

Air| (HL) ^5 H L H (L H) ^5| Sub

Figure 2 and Figure 3 are about the reflectance, transmittance and group delay of the device. Clearly seen from Figure 2 the reflectance and transmission of the design are very high. From Figure 3, we can easily find the group delay is flat within the bandwidth of reflectance, the ripples of the wave are so small and takes the values between (-50 to +50) *fs.*

Table 1 below shows layers and thickness as a function of layers materials for TiO_2/SiO_2 as high/low index. This regular quarterwave thin film stacks; spatial shift *Sx*can be easily calculated from the formula we presented before. Calculation is performed when the incident laser is in s-polarization state and the incident angle is 23.5°on the glass film stack interface.

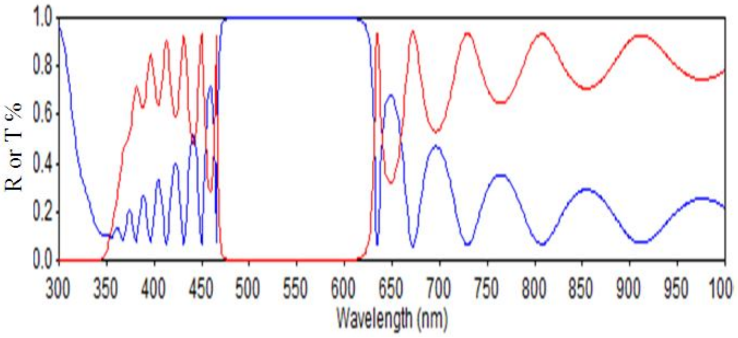

Figure 2: Reflectance and Transmission of design superprism structure.

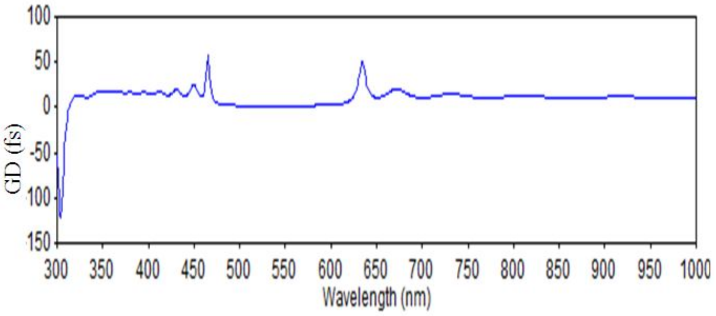

Figure 3: Group delay on Transmittance for design superprism structure.

Table 1: Layer structure of superprism in 1D.

No.	Material	Thickness	No.	Material	Thickness
1	TiO_2	58.611	12	SiO_2	92.613
2	SiO_2	92.613	13	TiO_2	58.611
3	TiO_2	58.611	14	SiO_2	92.613
4	SiO_2	92.613	15	TiO_2	58.611
5	TiO_2	58.611	16	SiO_2	92.613
6	SiO_2	92.613	17	TiO_2	58.611
7	TiO_2	58.611	18	SiO_2	92.613
8	SiO_2	92.613	19	TiO_2	58.611
9	TiO_2	58.611	20	SiO_2	92.613
10	SiO_2	92.613	21	TiO_2	58.611
11	TiO_2	58.611	22	SiO_2	92.613
12	SiO_2	92.613	23	TiO_2	58.611

Conclusion

The proposed 1D superprism is much simpler in structural complexity and, therefore, easier to design and fabricate. Like their 3D counterparts, the 1D superprism can exhibit giant dispersions over small spectral bands that can be tailored by judicious structure design and tuned by varying incident beam direction. These properties can find applications in telecommunications and electronics, as the current microelectronic technologies demand new building blocks to integrate photonics in their hot and slow semiconductor devices.

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