THIN-FILM (DE)MUX BASED ON GROUP-VELOCITY EFFECTS

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Abstract *We demonstrate that group-velocity effects in a single 66-layer dielectric stack can be used to separate four channels by spatial beam shifting. A nearly linear 100-µm shift is experimentally achieved between 827 and 841 nm.*

WDM systems create a strong need for compact wavelength splitting devices that can be easily manufactured. We focus here on thin-film structures, since they are easy to fabricate with well-known technology. In contrast to typical dielectric interference filters though, we use group velocity effects to separate multiple beams of different wavelengths with a single multilayer structure. These group velocity effects are similar to the "superprism effect" observed in one-dimensional [1,2], two-dimensional [1], and three-dimensional [3] photonic crystals.

In certain wavelength regimes of a photonic crystal, a rapidly changing group velocity angle causes beams of different wavelengths to propagate in different directions. A periodic dielectric stack behaves as a one-dimensional photonic crystal and exhibits the "superprism effect" close to the edge of each stop band. Unfortunately, such a thin-film one-dimensional photonic crystal is not very useful for practical purposes for two reasons [4]. One is that the dispersion is highly non-linear with wavelength leading to distorted beams and non-uniform channel spacing. Secondly, a large portion of the power is reflected off the front of the dielectric stack due to the operation close to the stop band and only the beam entering the stack sees the dispersion. Here we demonstrate that a non-periodic thin-film dielectric stack can be designed to obtain the same type of group velocity effect with superior wavelength splitting properties.

Fig. 1 shows a schematic of our thin-film device. Light is incident onto the dielectric stack from the substrate side. Within the dielectric stack different wavelengths propagate at different group velocity angles. Thus, beams of different wavelength are spatially separated along the x-direction. In order to achieve a higher spatial separation at the output, multiple bounces are performed in the stack.

We designed and experimentally tested a 66-layer dielectric stack consisting of alternating layers of SiO_2 (n=1.46 at 830 nm) and Ta_2O_5 (n=2.06) with a total stack thickness of 13.4 µm. To prevent reflection off the front of the stack, we used a "tapered" Bragg stack as the starting design [5]. In such a Bragg stack the periodicity is slowly "turned on" by increasing the amount of high index material in each period. This is equivalent to tapering a surface corrugated structure [1]. Next we employed numerical refinement techniques [6] on the tapered Bragg stack to achieve a design with a linear shift along the exit interface as a function of wavelength. Since we operate the dielectric stack under an angle, the device is polarisation sensitive. Our design only works for p-polarisation.

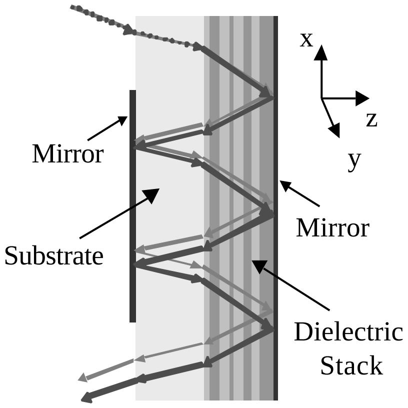

Fig. 1. Device schematic (not to scale). Different wavelengths propagate at different group propagation angles within the dielectric stack and are spatially separated. In our experiments the right mirror was not yet deposited.

We tested the design by focusing the p-polarised light of a tuneable continuous wave Ti-Sapphire laser at a 54º incidence angle onto the structure. We used a 9.2 µm spot size corresponding to a 15.7 µm spot size along the x-direction. The substrate was lapped to 1 mm and a gold coating applied. As we are operating close to the Brewster angle, no antireflection coating is needed. To increase the dispersion we used eight bounces through the structure. This corresponds to a total device length in the x-direction of approximately 11 mm. In the y-direction the device only needs to be as wide as the incident beam. For a linear shift with wavelength all beams of different wavelength focus at the exit interface for the x-direction. We used a lens to project a magnified image of the exit interface onto a CCD camera. As the beam propagates through a plate at an angle, the focal points for the x- and the y-direction are not identical anymore leading to elongated beam shapes. To obtain a simultaneous focus in both directions a cylindrical lens would be needed.

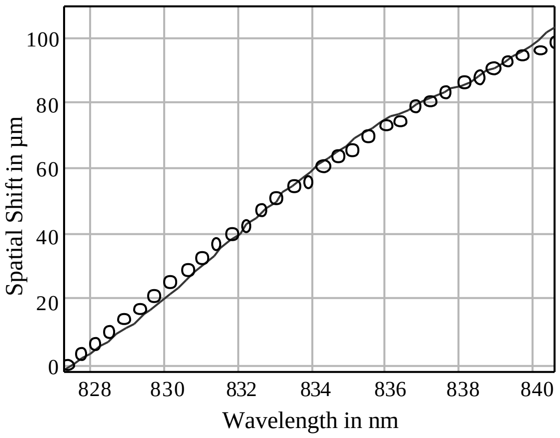

Fig. 2. Shift along the x-direction as observed in experiment (circles) and calculated theoretically (solid line) for a 54º incidence angle and eight bounces through the structure.

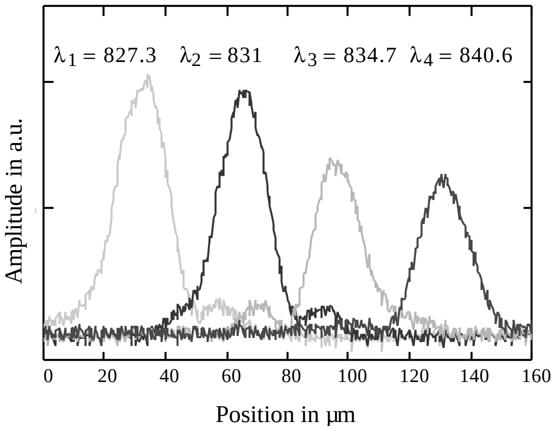

Fig. 3. Four overlapped CCD traces along the x-direction. Using eight bounces through a single 66-layer dielectric stack at a 54º incidence angle we can separate four beams by their Gaussian beam widths. The channel wavelengths given in the plot are in units of nm.

In Fig. 2 the experimentally observed shift along the x-direction is shown. Also plotted is the theoretically expected shift. A quite linear spatial shift with wavelength is achieved allowing for nearly uniform channel spacing. Fig. 3 demonstrates that this shift can be used to separate four beams by their Gaussian beam width. The first three beams have a channel spacing of 3.7 nm. The spacing between the third and fourth channel is with 5.9 nm larger due to the reduced dispersion. The amplitudes of the beams are decreasing with wavelength, because we have not yet applied the gold coating to the stack side. This coating was omitted to allow for easier testing of the dielectric stack. The dielectric stack itself has a lower reflectance for larger wavelengths. Simulations predict a significantly increased reflectance with the gold coating applied. We are currently investigating the slight beam distortions visible in Fig. 3.

To reduce the crosstalk between the four channels, the beams could be focussed to a smaller spot size or more bounces could be performed through the structure. We chose to operate the design around 830 nm because of the available tunable laser, but it can be easily scaled to the 1300 nm or 1550 nm wavelength regime. Upon scaling all layers by the same factor, the spatial shift and the channel spacing are scaled as well. Therefore, the 100 µm shift and 4 nm channel spacing at 830 nm corresponds to a 157 µm shift and 6.3 nm channel spacing at 1300 nm, and to a 187 µm shift and 7.5 nm channel spacing at 1550 nm. Assuming an equal amount of focussing, the spot size scales by the same factor leading to the same amount of crosstalk between channels.

Here we have shown that a thin-film dielectric stack can be designed to exhibit a rapid change in the group propagation angle with wavelength. We demonstrated a nearly linear 100 µm shift over a 13 nm wavelength range. This device principle is not limited to this type of shift and wavelength range. Thin-film filter design techniques can be used to design a wide range of dispersion characteristics with wavelength. The dielectric stack could for example be designed to exhibit dispersion over a much narrower or broader wavelength range, or the dispersion could be designed to be linear with frequency instead of wavelength or even possibly staircase-like. There is a physical limit though to the dispersion obtainable over a desired wavelength range for a given number of bounces through the structure and a given material system and incidence angle. In conclusion group velocity effects in thin-film filters can be utilised to obtain compact cost-effective wavelength multiplexing and demultiplexing devices that use a single multilayer structure to separate multiple beams.

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