Planar arrayed waveguide device structure for 2D wavelength demultiplexing

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Abstract: Simple arrayed waveguide grating (AWG) structure which demultiplexes wavelengths to output ports arranged in 2D plane is proposed. The planar geometry provides easy fabrication of the device. An AWG is connected to a device forming a 2D aperture array, which generates smaller dispersion in orthogonal direction against that generated by AWG.

Keywords: arrayed waveguide grating, wavelength demultiplexer, virtual image, waveguide mirror

Classification: Photonics devices, circuits, and systems

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1 Introduction

Many types of wavelength demultiplexers have been proposed for WDM optical communication and other applications such as wavelength monitoring. Most of the devices separate wavelengths into output ports arranged in a line (1D demultiplexing). When we can demultiplex the wavelengths into output ports arranged in two-dimensional (2D) plane, the number of ports could be increased dramatically. Device configurations using two cascaded wavelength

dependent light beam steering devices each assigned for orthogonal spatial axis (x and y axis) have been known for some time. Recently we proposed a method using only a single device to realize 2D wavelength demultiplexing [1]. A structure generating different spatial dispersions for x and y axis respectively, with novel employment of Free Spectral Range (FSR), enables 2D wavelength demultiplexing. The concept has been employed to an arrayed waveguide device and thorough analysis has been reported [2]. However, the structure requires stacking of many layers making the method impractical for fabrication. In this report we propose a device using only a single arrayed waveguide device in a simple planar structure [3].

2 Device configuration

The device we propose (Fig. 1) is the planar waveguide version of the device we reported in 2D structure [1]. Instead of using a free space light beam, we use guided light in a planar waveguide propagated in appropriate direction for generating required light path difference by a waveguide array [3]. A lens not shown in Fig. 1 is required to focus the demultiplexed light beam into output ports. The 3D structure in Ref. 1 generates discrete light focusing spots for each phase matching wavelength, but in 2D structure, the spot is scanned along a line folded back at the end of a FSR just like a deflected electron beam in the cathode ray tube (CRT) for a television.

Fig. 1. Planar arrayed waveguide device structure for 2D wavelength demultiplexing.

In the 2D demultiplexing method, the beam spot position shift in the x axis for different wavelengths can be larger than that for the y axis. To realize a 2D wavelength demultiplexing, several wavelengths should be directed into a single x (and y) coordinate. The multiple FSR is used for this purpose. The 2D wavelength-demultiplexing device requires a section that generates large spatial dispersion associated with FSR and a section with smaller spatial dispersion. An arrayed waveguide grating (AWG) [4] is connected to a planar waveguide grating structure for creating a virtual image 2D aperture array

(Fig. 2). The AWG generates a large dispersion in the x axis. The 2D aperture array generates smaller dispersion in the y axis. Many types of grating structures such as UV induced grating or surface grating [5, 6] can be used as the partial reflecting mirrors. The bulk holographic grating or even a conventional reflection grating can also be used as a 2D aperture generator.

Fig. 2. Virtual 2D light aperture array generated by planar waveguide Bragg grating.

3 Filter response

We obtain the total light field I as a function of beam direction in x and y axis (Θ_x and Θ_y), by summing the light field from each aperture over the waveguide array number r and grating number q .

$$I = \sum A_{qr} \exp[jkr(-d \sin \Theta_x + DL_a)] \exp[jkq\Lambda(\sin \Theta_y + 1) \cos \Theta_x] \\ \times \iint B(x, t) \exp[jk\{-x \sin \Theta_x + t \cos \Theta_x[-\cos(\Theta_y - \Theta + \pi/2) \\ + \cos(\Theta)]\}] dx dt \quad (1)$$

where k is the light wave number, t is the coordinate on a grating mirror, Θ is the mirror angle, d is the waveguide output separation of AWG and DL_a is the adjacent path length difference in arrayed waveguide. The grating period is Λ .

When the light power A_{qr} is equally divided among 2D aperture array and rectangular light power distribution $B(x, t)$ in each aperture is assumed, the light field becomes,

$$I = A \{ \sin[kN_w(-d \sin \Theta_x + DL_a)/2] \sin[kM_w\Lambda(\sin \Theta_y + 1) \cos \Theta_x]/2 \\ / \{ \sin[k(-d \sin \Theta_x + DL_a)/2] \sin[k\Lambda(\sin \Theta_y + 1) \cos \Theta_x/2] \} \\ \times \sin(-kS \sin \Theta_x/2) \sin[kT[-\cos(\Theta_y - \Theta + \pi/2) + \cos(\Theta)] \cos \Theta_x/2] \\ / \{ (-kS \sin \Theta_x/2) [kT[-\cos(\Theta_y - \Theta + \pi/2) + \cos(\Theta)] \cos \Theta_x/2] \} \} \quad (2)$$

where S is the aperture width at the end of the waveguide array and T is the cross sectional length of the slanted grating aperture. N_w is the number of waveguides in AWG and M_w is the number of grating along a light path. The maximum output is centred on $\Theta_y = 2\Theta - \pi/2$. The mirror angle Θ should be tilted in accordance with Θ_y designed to attain desired performance. The output becomes the same as that of the conventional AWG for each spatial axis.

The beam steering angle change caused by wavelength shift $\Delta\lambda$ in x axis $\Delta\Theta_x$ and y axis $\Delta\Theta_y$ are derived as $\Delta\Theta_x = -S_x\Delta\lambda/(nd)$ and $\Delta\Theta_y = S_y\Delta\lambda/(n\Lambda \cos \Theta_x \cos \Theta_y)$ respectively with n being the refractive index. Here S_x and S_y are interference order for x axis and y axis respectively. The half width of the filter response peak is defined by $\Delta\lambda_x = \lambda/(N_w S_x)$ for the x axis which is narrower than that for the y axis $\Delta\lambda_y = \lambda/(M_w S_y)$.

4 Design procedure

The device is designed using the filtering performance deduced from Eqs. 1 and 2. We consider a device demultiplexing NM wavelengths into $N \times M$ array of light beams. N is equal to the resolvable wavelength number in a FSR along the x axis and M the resolvable wavelength number along the y axis. A condition $N_w > 2N$ and $M_w > 2M$ is required to avoid the overlap between light beams.

The interference order, S_x for x axis, at centre wavelength is determined from wavelength resolution and number of resolvable wavelengths in FSR. The interference order for y axis is determined from the total wavelength scan range $D\lambda_{sc}$. These lead to $S_x = [\lambda_0/(D\lambda_{sc}/M)]$ and $S_y < (\lambda_0/D\lambda_{sc})$ where λ_0 is the centre wavelength. For the first order grating $S_y = 1$.

4.1 AWG

The array spacing d is defined from the required beam divergence angle $D\Theta_x$ along the x axis. With $D\Theta_{sc}$ being the angle scan range of the light beam for 2D demultiplexing, $D\Theta_x = D\Theta_{sc}/N$. The angle $D\Theta_{sc}$ is limited by the light divergence angle of each aperture. The array spacing is obtained by $d = 2\lambda_0/(N_w n D\Theta_x)$. The length difference DL_a is defined by beam direction along x axis Θ_{xa} at an anchor wavelength λ_a and S_x . So that, $DL_a = (S_x \lambda_a - \Theta_{xa} nd)/n_a$, where n_a is the effective refractive index of the waveguide array.

4.2 Grating

The light beam angle shift along y axis, induced by wavelength shift of a FSR, should be larger than divergence angle of the light beam along y axis $D\Theta_y$. This restriction defines the number of grating M_w . The number of grating is calculated by $M_w = 2S_x/S_y$. We make the beam divergence angle along the x and y axis ($D\Theta_x$ and $D\Theta_y$) equal, so that the light beam has circular cross section. This sets the diffraction direction Θ_{y0} at center wavelength as $\cos \Theta_{y0} = 2/[S_x D\Theta_x + 1/(S_x D\Theta_x)]$. Finally, the grating period Λ is defined by beam direction along y axis Θ_{ya} at an anchor wavelength λ_a and S_y . Thus,

$\Lambda = S_y \lambda_a / [n_g (\sin \Theta_{ya} + 1) \cos \Theta_{ya}]$ where n_g is the refractive index of the grating portion. The beam angle difference between those for the anchor and center wavelength is calculated by using equations for $\Delta \Theta_x$ and $\Delta \Theta_y$ described in section 3.

The angle Θ_{y0} limits the practical design range. For easiness of fabrication, $\Theta_{y0} < 1.2$ rad is desirable, which sets an upper limit for parameter $S_x D \Theta_x = (M/N)[D \Theta_{sc} / (D \lambda_{sc} / \lambda_0)]$ to be less than 4. When the device is designed for a narrow wavelength range, the light beam angle scan range should be also narrow accordingly.

5 Simulation

Example of calculated 2D light spot array for wavelength channels is shown in Fig. 3. The wavelength ranges from 1.52 to 1.58 μm . Corresponding interference order for x axis is from $S_x = 405$ to 390 and $S_y = 1$ for y axis. The AWG portion has 32 waveguide array; path length difference DL_a of 616.4 μm and output port separation $d = 9.3 \mu\text{m}$. The grating portion has grating with 370 mirrors with period Λ of 0.803 μm . The light beam divergence angle generated by 2D aperture array was 0.01 rad. A grating fabricated with refractive index change of $dn \sim 10^{-3}$ is required to reflect sufficient light out of the planar waveguide to attain 1 dB loss, which is approximately estimated by $dn = n_g [(1 - R)^{-1/2 M_w} - 1] / 2$ where R is the total fraction of the reflected light power. The required refractive index change becomes lower for narrower wavelength range and larger wavelength channels due to the increase in the number of mirrors.

Fig. 3. Simulated light spot center of 2D wavelength demultiplexing from 1520 to 1580 nm wavelength.

Since the dispersion in y axis is a function of angle Θ_y the light spot interval shows a angle dependence in this direction. The light beam shape and filter response peak shape remains the same through out the wavelength range as revealed by simulation.

The chip size for high index contrast waveguide is approximately 1 square centimeter in which the grating portion occupies an area of 0.3 square millimeter. The distance between chip (lens) and focal plane is 5 mm assuming 0.05 mm demultiplexed light spot separation.

6 Conclusion

Simple arrayed waveguide grating structure that demultiplexes wavelengths to output ports arranged in 2D plane have been reported. The planar arrangement enables easy fabrication. An AWG is connected to a grating device forming a virtual image 2D aperture array, which generates smaller dispersion in different direction than that of AWG. The 2D wavelength demultiplexing was verified by calculation. Design parameters such as the waveguide mirror angle and spacing between mirrors were calculated. The design parameters were in reasonable value range for fabrication to obtain a device with several-hundred-wavelength channels.