ABSTRACT

Wavelength division demultiplexing using acousto-optic cells as a dynamic diffraction gratings is proposed. The system has the advantage of high resolution, relatively low insertion loss, tunability for a wide range of wavelengths, and tunability for the intensity variation of the deflected beams. Analysis of the demultiplexing system for five channels in the 0.8 pm region is discussed and computer simulation results are presented.

1. INTRODUCTION

Wavelength-division-multiplexing/demultiplexing (WD MUX/DMUX) technique allows simultaneous transmission of multiple optical channels at different wavelengths through a single optical fiber. It gives the optical communication system the advantages of increased transmission capacity, reduced cost, feasibility of simultaneous transmission of signals with different modulation schemes, and the ability to increase the system capacity after fiber installation.

In WD MUX/DMUX systems, diffraction gratings are advantageous over other devices such as prisms and filters. An acoustic cell driven by a sinusoidal electric signal acts as a diffraction grating and can be used as a light deflector. Acousto-optic deflectors were proposed for wavelength division multiplexing switches [1]. In this paper, we are proposing a novel wavelength division demultiplexing system using acousto-optic cells. An acousto-optic diffraction grating (AODG) is advantageous over manufactured grating since the directions of the deflected light beams can be controlled by changing the frequency of the drive signal and the light intensity of these beams can be adjusted by changing the power of the drive signal. The former advantage is important since the increase in the insertion loss due to wavelength drift of the light sources (caused by temperature changes) can be alleviated. This system also has the flexibility for replacing the light sources with others at different wavelengths without the need to replace the MUX/DMUX systems.

II. AODG CHARACTERISTICS

Consider the schematic shown in Fig. 1 in which an acoustic cell of length L and effective width W is driven by an electric signal with frequency f. An optical beam with wavelength \( \lambda \) illuminates the cell at an angle \( \theta \). The normalized intensity of the first-order diffraction (assuming isotropic diffraction) is given by [2]

\[
I_1 = \eta \sin^2 \left[ \eta + \left( \frac{\Delta k_W W}{2} \right)^{1/2} \right],
\]

where

\[
I_{\text{max}} = \sin^2 \eta^{1/2},
\]

and

\[
\eta = \frac{\pi^2 M_a}{2\lambda^2} \frac{P_a W}{Hc_0 \rho^2 \theta}.
\]

\( M_a = \frac{\eta}{\rho \nu^2} \) is the AO figure of merit, \( P_a \) is the acoustic power launched by the drive signal, \( H \) is the effective height of the cell, \( \nu \) is the acoustic velocity in the interaction medium, \( n, \rho, \) and \( p \) are the index of refraction, the density, and the photoelastic coefficient, respectively, of that medium, and \( \Delta k_W \) is the momentum mismatch which is given by

\[
\Delta k_W = \frac{-\pi \lambda}{n \lambda^2 \cos \theta} \left( 1 - \frac{2n \lambda}{\lambda^2 \sin \theta} \right),
\]

where \( \lambda = \frac{\nu}{f} \) is the acoustic wavelength.

Momentum match \( (\Delta k_W = 0) \) can be obtained at the Bragg angle of incidence \( \theta_B \) given by

\[
\theta_B = \theta_c = \sin^{-1} \frac{\lambda f_c}{2\nu n^2}.
\]

In this case, the diffraction efficiency has its maximum value \( \sin^2 \eta^{1/2} \) and, therefore, theoretically 100% diffraction efficiency can be obtained for \( \eta^{1/2} = \frac{\pi}{2} \). However, momentum mismatch can arise for any values of \( \lambda, f, \) and \( \theta \) such that Eq. (5) is not satisfied. In the case of momentum mismatch, the diffraction efficiency is reduced by the factor \( \sin^2 \left( \frac{\Delta k_W W}{2} \right) \).

It was shown [2] that in the case where \( \theta = \theta_c \) and \( \lambda = \lambda_c \) while f is changed around \( f_c \), the 3-dB bandwidth \( \Delta f \) of the diffraction efficiency is given by

\[
\frac{\Delta f}{f_c} = \frac{18}{Q^2},
\]

where
The focal plane is given by
\[ Q = \frac{2\pi \lambda f c^2 W}{n V^2} \]  \hspace{1cm} (7)

It can be shown that in the case where \( f = f_c \) and \( \lambda = \lambda_c \), while \( \theta \) is changed around \( \theta_c \), the 3-dB angular width of the diffraction efficiency is given by
\[ \Delta \theta_c = \frac{\Delta f}{f_c} \]  \hspace{1cm} (8)

Similarly, in the case where \( f = f_c \) and \( \theta = \theta_c \), while the illumination wavelength is changed around \( \lambda_c \), the 3-dB wavelength width of the diffraction efficiency is given by
\[ \frac{\Delta \lambda_c}{\lambda_c} = \frac{\Delta f}{f_c} \]  \hspace{1cm} (9)

Fig. 2 shows the diffraction efficiency given by Eq. (1.a) for the previously discussed three cases. The following parameters are assumed: \( n = 2.26 \), \( W = 2.5 \) mm, \( M_2 = 1200 \), \( H = 2 \) mm, \( f_c = 50 \) MHz, \( \lambda_c = .84 \) \( \mu \)m, \( \theta_c = 8^\circ \), and \( P_a = .213 \) W. The figure is in good agreement with the approximate relations given by Eqs. (6), (8), and (9).

The light intensity distribution of the first-order diffraction in the back focal plane of a focusing lens with focal length \( F \) and positioned just behind the acoustic cell is given by
\[ I_1(x') = I_1 \sin^2 \left[ \frac{2D}{\lambda F} (x' + F \sin \theta - \frac{\lambda_f}{F} F) \right], \]  \hspace{1cm} (10)

where \( I_1 \) is given by Eq. (1) and \( D \) is the diameter of the light beam illuminating the acoustic cell. Thus, the diffracted light has a sinc\(^2(\cdot)\) distribution with maximum value \( I_1 \) positioned at \( x' \) given by
\[ x' = \left( \frac{\lambda_f}{F} - \sin \theta \right) F, \]  \hspace{1cm} (11)

and 3-dB beamwidth given by
\[ \Delta x' \approx \frac{\lambda_c F}{D}, \]  \hspace{1cm} (12)

which increases linearly with \( \lambda_c \). The linear dispersion in the focal plane is given by
\[ \frac{\Delta f}{\Delta x'} = \frac{nV}{F}. \]  \hspace{1cm} (13)

III. WAVELENGTH-DIVISION DEMULTIPLEXING

Eq. (11) shows that the deflected light beam has an angle \( \theta' \) given by
\[ \theta' = \frac{\lambda_f}{F} \sin \theta, \]  \hspace{1cm} (14)

which is linearly proportioned to both \( \lambda \) and \( f \).

Assume the light beam to be demultiplexed has \( N \) different wavelengths centered around \( \lambda_c \), and incident at the acoustic cell at an angle \( \theta_c \). The frequency of the drive signal is \( f_c \) that satisfy Eq. (5). In this case, there exists \( N \) deflected light beams (representing the first order diffraction of the incident beam) at \( N \) different deflection angles according to the relation
\[ \theta_i' = \frac{\lambda f_c}{n V} \sin \theta_c, \hspace{1cm} i = 1,2, \cdots, N. \]  \hspace{1cm} (15)

The separation between two adjacent beams in the back focal plane is
\[ d = \frac{\Delta \lambda_c}{n V} f_c F, \]  \hspace{1cm} (16)

where \( \Delta \lambda_c \) is the wavelength spacing between the channels. Rayleigh resolution criteria implies that \( d \) should be equal to or greater than \( \Delta x' \), that is
\[ \Delta \lambda_c > \frac{\lambda_c}{D} \frac{F}{f_c} = \Delta \lambda_{min} \]  \hspace{1cm} (17)

The light from the input fiber is collimated by a lens and then illuminates the acoustic cell. Assuming the input fiber has numerical aperture \( NA \), the lens has focal length \( F_1 \), and the medium between the fiber and the collimating lens has index of refraction \( n_1 \), the collimated light beam has diameter \( D \) given by
\[ D = \frac{2f_1 (NA)}{n_1} \]  \hspace{1cm} (18)

Since \( I_1 \) depends upon the momentum mismatch, the peak value of the light intensity is maximum at the central channel with \( \lambda_c \) (since the momentum mismatch is zero) and the peak value decreases as \( \lambda \) deviates for \( \lambda_c \) for the other channels. Fig. 3 shows WD DMUX of five wavelengths. The following parameters are used: \( \lambda_c = .84 \) \( \mu \)m, \( f_c = 50 \) MHz, \( \Delta \lambda_c = 20 \) nm, \( v = 620 \) m/s, \( n = 2.26 \), \( W = 2 \) mm, \( H = 2 \) mm, \( W = 2.5 \) mm, \( F = 2 \) cm, \( \theta_c = 86^\circ \), \( P_a = .0221 \) watt, \( n_1 = 1 \), \( NA = .11 \), and \( F_1 = 3 \) cm. The spacing between the adjacent channels in the back focal plane is 14.27 \( \mu \)m which is suitable for the use of photodiode array in integrated optic technology and better resolution can be obtained by increasing \( D \). From Eq. (13), the linear dispersion results in an increased insertion loss which may arise since light sources are wavelength temperature dependent \((<0.2 \) nm/°C). However, the effect of wavelength drift \( \Delta \lambda \) on deflection angle \( \phi' \) can be compensated such that \( \phi' \) remains constant for the same deflected beam. This can be achieved by changing the frequency of the drive signal by \( \delta f \) where
\[ \delta f = \frac{f}{\lambda} \delta \lambda. \]  \hspace{1cm} (19)

Since \( f \) can be changed within a wide range without significant effect on the diffraction efficiency, this system has a wide tuning range for wavelength variation. The insertion loss is due to the lenses, the grating, and the coupling to the output. The grating loss is due to surface reflection, optical transparency of the interaction medium, and the momentum mismatch. The loss due to reflection is .09 dB since the acoustic cell has antireflection coating 1% per surface. The optical transparency of the cell is > 95% and therefore the loss is about .2 dB. Fig. 3 shows the light intensity distribution...
for five demultiplexed channels. The central channel has no mismatch loss while the first, second, fourth, and fifth channels have $4$, $1.09$, and $0.38$ dB, respectively. Thus, the total loss of the grating is $2.9$ to $6.9$ dB. The crosstalk between channels is about $0.25$ dB and larger attenuation can be achieved by increasing the beam diameter $D$.

The collimating lens has a loss $\sim 0.4$ dB while the focusing lens has a loss $\sim 0.25$ dB. The coupling loss depends upon the light sensitivity of the receiving region of the photodiodes and the angle of incidence of the light beam on the corresponding detector.

Eq. (10) shows that the light intensity depends upon $I_1$, which can be controlled by the radio frequency (rf) power of the drive signal. Thus, the light intensity of the deflected light beams can be maintained constant, within some changes in the intensity of the incident beam, through a feedback loop that adjusts the rf power. Assuming the transducer efficiency $E_t = 0.65$, the required rf power is $P_{rf} = P_a/E_t = 0.328$ W. Assuming the acoustic cell has $\Delta \lambda = \lambda / \beta = 0.3$, the allowed wavelength width is $\Delta \lambda = 252 \mu m$ and, therefore, the allowed number of channels is $\Delta \lambda / \lambda = 12$ channel. Fig. 3 shows that $\Delta \lambda$ can be further decreased and, consequently, the number of possible channels increases.

4. CONCLUSION

Using acoustic cells as diffraction gratings in WD DMUX system provides the advantage of high resolution since long acoustic cells are commercially available. Fig. 3 shows that according to Rayleigh resolution criteria, $\Delta \lambda_{\text{min}} \leq 3.6$ nm. Better resolution can also be achieved by increasing the light beam diameter which requires large focusing length for the collimating lens or using input fibers with larger numerical aperture (as in multi-mode fibers). The system is tunable for wavelength variation over wide range such that the direction of a deflected beam remains constant regardless of the wavelength variation. Thus, the insertion loss that would arise due to this variation is avoided. This is important since the wavelength of a laser diode is temperature dependent. Also, the light intensity of the deflected beams can be kept constant within some variation of the intensity of the input beam.

5. REFERENCES


Fig. 1. Acousto-optic deflector geometry.

Fig. 2. Diffraction efficiency vs. relative frequency (solid curve), angle of incidence (dotted curve), and wavelength (dashed curve).

Fig. 3. Light intensity distribution for the five demultiplexed channels.