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Feedback correction of angular error in grating READOUT

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ABSTRACT

Angular and wavelength READ beam errors in holographic interconnection systems are often a recurrent problem. Several strategies have been proposed to minimize or eliminate such READOUT misalignments. Some years ago, Chatterjee and co-workers proposed a method involving READ beam wavelength tuning to correct output angular errors. In this paper, we investigate the possibility of using an acousto-optic (A-O) Bragg cell with optoelectronic feedback to dynamically correct the scattered beam for deviations in the incidence direction of the READ beam of a hologram. The concept here is based on an acoustic frequency feedback strategy used recently by Balakshy and Kazaryan for laser beam directional stabilization. In the dynamic and adaptive method being proposed here, an acousto-optic Bragg cell is placed between the READ beam and the hologram. A photo-detector placed after the Bragg cell enables the estimation of scattered efficiency and hence (from the READ dephasing-based diffraction efficiency), the amount of the angular deviation. An algorithm for implementing the above scheme, to be used in a practical setup, is proposed and the results of numerical simulations are presented along with possible extensions to wavelength error correction and other applications.

Keywords: acousto-optics, optical feedback, stabilization, READ misalignments, efficiency, Bragg diffraction

1. BACKGROUND AND MOTIVATION

The various effects of bistability (leading to multistability and chaos) emerging from feeding back the intensity of the diffracted output order to generate nonlinear dynamics have been investigated extensively [1-4]. The intensity of the first order light at the previous instance ($I_1(n)$), at the detector is added to a bias α_0 (after being multiplied by a gain β) to change the effective α which affects the intensity of the first order light in the following manner:

$$I_1 = I_{inc} \sin^2\left(\frac{\alpha}{2}\right) \quad (1)$$

The above may be incorporated into the following feedback equation:

$$I_1(n+1) = I_{inc} \sin^2\left(\frac{\alpha_0 + \beta I_1(n)}{2}\right), \quad (2)$$

where n represents the feedback iteration step.

This difference equation, as well as a related delay differential equation, have been investigated for interesting dynamics for varying values of β and time delay. The initial impetus to the idea behind this paper was to extend the above ideas to feeding back frequency and investigating the nonlinear dynamics of the direction of the laser beam. Some initial thoughts were related to applications such as laser tracking whereby the beam would move chaotically / randomly (more appropriately pseudo-randomly) and then zero in on interesting targets. However target location in 3-D by this method turned out to be very complex. In a related context, it was found that the dependence of the diffraction efficiency of holographic phase gratings on READ angular and wavelength errors has been investigated by several techniques [4-8]. The angular misalignment of the output has also been modeled as a function of the two READ parameters mentioned earlier [4,6,7,9].

In ref. [10], Chatterjee *et al.* have derived a transfer function for acousto-optic Bragg diffraction of arbitrary profiled beams using an angular spectrum and Fourier approach based on multiple plane wave scattering and Feynman diagram concepts [11]. Thus, the spatial diffraction pattern for any profiled input beam can be found once the transfer function of the Bragg cell is known. The definition for the transfer function derived in the above work is consistent with a dephasing-based diffraction efficiency formula for a Bragg cell.

Chatterjee and co-workers [4,7,9] have used the formalism of wave vector triads to estimate angular errors in holograms as a function of both angular and wavelength misalignments. In their work, a strategy of compensating for angular misalignments by READ wavelength tuning has been suggested. Recently, Balakshy and Kazaryan [12] have used the idea of frequency feedback for laser beam direction stabilization. Their work further investigates the nonlinear dynamics of the system after incorporation of feedback.

This paper outlines an extension of the concepts mentioned above whereby frequency feedback based on diffraction efficiency is suggested as a more versatile, dynamic and realizable alternative to the wavelength tuning method for correcting READ angular errors proposed elsewhere. Although directional correction and stabilization may have a variety of potential applications, this work specifically targets its use in the context of holographic interconnection systems involving multiple sources and/or receivers, and other multiplexed optical communication systems. Clearly, in these applications, maintaining the direction of scattering is critical to avoiding problems caused by cross talk. Bragg angle mismatch caused by misalignment and non-uniform grating formation are among the main obstacles to the above goal of maintaining the direction of interconnection beams. The method proposed in this paper makes it possible to restore the scattered output direction both dynamically and adaptively for arbitrary (albeit discrete and relatively small angle) deviations from the Bragg angle.

It is proposed that the deflection properties of the acousto-optic Bragg cell may be appropriately exploited to deflect the misaligned incident READ beam such that the scattered beam from the sound cell will arrive at the hologram at the correct angle. As shown later, the Bragg cell is placed before the hologram, the angular deviation is detected, and subsequently the output beam direction is corrected using the necessary, feedback-corrected acoustic frequency to drive the Bragg cell. The scheme outlined in this paper has the advantage of simplicity in that it avoids having to contend with the efficiencies of the hologram and the acousto-optic Bragg cell together. Thus as far as the hologram is concerned, the error correction is through a feed-forward mechanism.

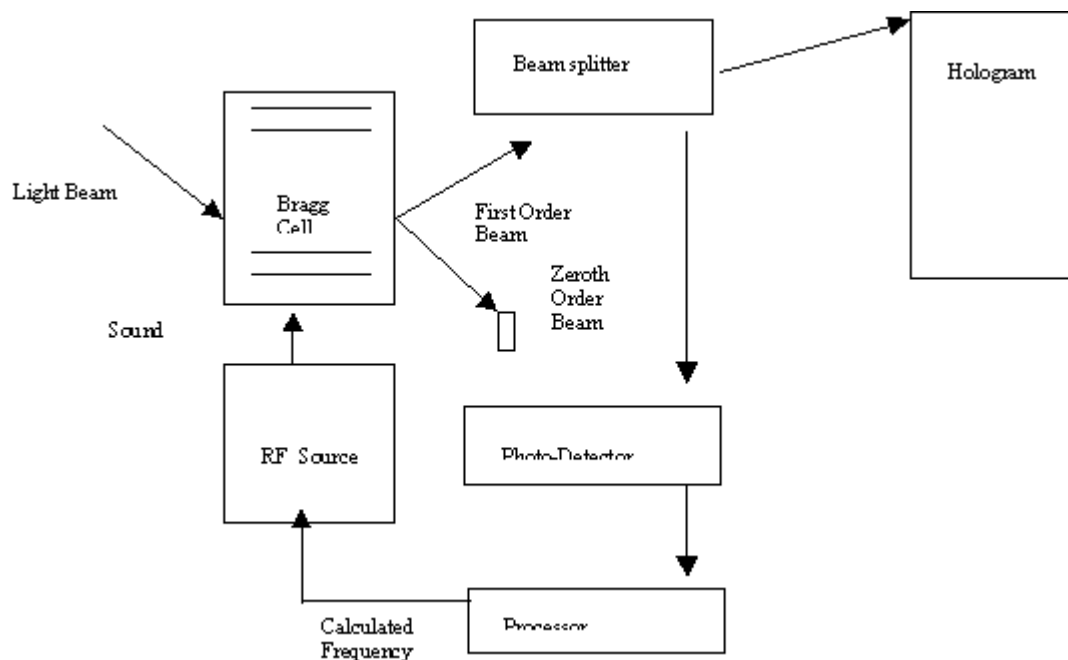


Fig.1. Schematic diagram showing angular correction via acousto-optic feedback.

In Fig.1, we show the overall schematic of the physical arrangement for acousto-optic frequency feedback for angular stabilization. The figure is self-explanatory; note that the stabilized laser beam, upon diffraction from the A-O cell, reaches an interconnection hologram at the requisite angle of incidence.

As is well-known, the expression of the diffraction efficiency as a function of the angular deviation is of the overall form of a sinc-squared function. Moreover, the dependence on angular deviation is also independent of the sign of the deviation, so that both positive and negative deviations would yield the same intensity. It was also found in the course of the analysis that once the output direction is restored, the current incidence angle is still not Bragg-matched, even though the difference between the Bragg angle and the incidence angle reduces. Also, since the Q factor in the efficiency formula is dependent on the acoustic frequency, the intensity relationship based on the efficiency needs to be updated following each incremental restoration of output angle for discrete input angular deviations. Also, after the first error correction, the subsequent diffraction efficiency will measure the deviation of the current incidence angle from the current Bragg and *not* from the original incidence angle for which the light beam restoration was carried out. Therefore, one must keep track of changing (effective) Bragg angles in addition to changing Qs. An algorithm controlling the frequency of the sound cell driver in the feedback loop enables the above parametric re-adjustments to be carried out conveniently.

2. ANGULAR ERROR CORRECTION AND BEAM STABILIZATION ALGORITHM

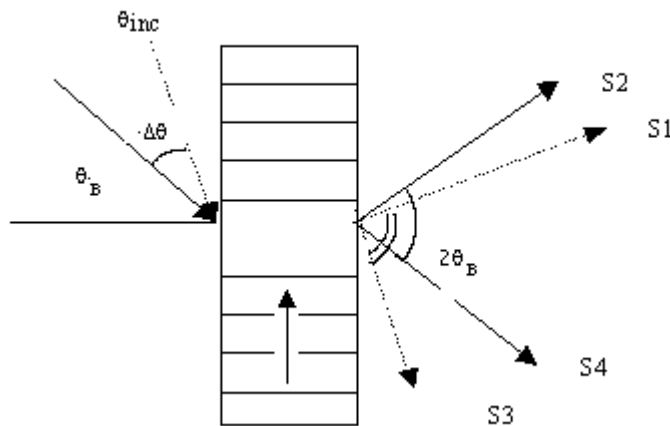


Fig.2. Bragg cell showing READ beam and output misalignments.

Note that in the entire paper, clockwise angles and angular deviations from the positive horizontal axis will be considered positive. Note that this is the reverse of the standard convention of clockwise angles being negative (as is traditionally done for up-shifted Bragg interactions); however, it is readily seen that this modified convention does not affect the physical results. In Fig.2, an A-O Bragg cell is shown with the undeviated, nominal Bragg incidence and scattering depicted by solid lines, and the corresponding near-Bragg (small deviation) incidence and scattering by dashed lines. In the figure, θ_B is the original, desired Bragg angle, θ_{inc} is the current incidence angle, and $\Delta\theta$ is the deviation from the (current) Bragg angle.

As we can see, S3 is in the same direction as the incident light. The incidence angle is off-Bragg in the clock-wise sense by $\Delta\theta$. The angle between the scattered output light direction and the undeflected output light direction is always twice the current Bragg angle, in our case $2\theta_B$. Hence, when the light is not incident at exact Bragg, the scattered light is in the S1 direction, which deviates from the desired direction S2 by $\Delta\theta$ in the clock-wise direction, the angle between S1 and S3 being also $2\theta_B$. The problem can be formulated as one involving simple feedback correction, with the goal of keeping the direction of the scattered (first order) beam fixed at S2, irrespective of the change in the incidence angle (within near-Bragg limits).

The problem can be broken up into two major steps:

- Estimating the angular deviation from the Bragg (in the above diagram, it is $\Delta\theta$) by measuring the diffraction efficiency which is expressed as a function of $\Delta\theta$; and
- Correcting for the input angular error by adjusting the Bragg angle via an appropriate change of the sound frequency at the RF source.

The deviation from the Bragg angle is estimated using the following well-known formula for diffraction efficiency:

$$\eta = \frac{\left(\frac{\alpha}{2}\right)^2 \sin^2 \left(\sqrt{\left(\frac{\delta Q}{4}\right)^2 + \left(\frac{\alpha}{2}\right)^2} \right)}{\left(\frac{\delta Q}{4}\right)^2 + \left(\frac{\alpha}{2}\right)^2}, \quad (3)$$

where the diffraction efficiency η is defined as the ratio of the scattered to incident light intensities;

$\delta = \frac{\Delta\theta_{B,before}}{\theta_{B,before}}$ is the fractional deviation from the (current) Bragg angle ;

$\theta_{B,before}$ is the (current) Bragg angle prior to each discrete frequency correction;

$\Delta\theta_{B,before}$ is the deviation of the incident angle from the current Bragg angle as defined;

α is the peak phase delay of light through the sound column; and

$Q = \frac{K^2 L}{k}$ is the so-called Klein–Cook parameter, (4)

where K refers to the acoustic wave number, L is the interaction length in the horizontal direction, and k refers to the optical wave number.

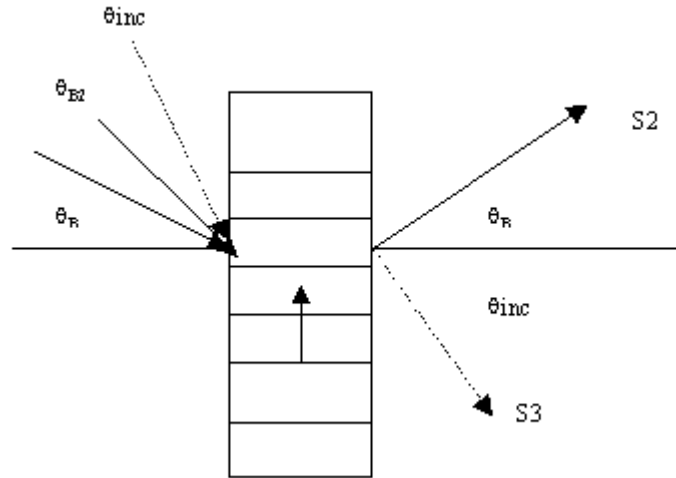


Fig.3. Bragg cell schematic following frequency feedback and angular stabilization.

As shown in Fig.3, which depicts the revised Bragg cell schematic following angular restoration, the scattered light beam follows the desired direction (S2) even though the incident angle is still not in the ideal Bragg direction and the zeroth order light emerges at S3 as before. Note that the zeroth order S3 is in the direction of the incident light. Thus, after correction, the angle between the zeroth and first order light beams (i.e., S3 and S2) is $\theta_B + \theta_{inc}$. Since the angle between the two orders is $2\theta_{B2}$ (where θ_{B2} becomes the new, equivalent Bragg angle), we may write:

$$2\theta_{B2} = 2\theta_{B,after} = \theta_B + \theta_{inc}.$$

From our earlier expression for θ_{inc} , we then have

$$\theta_{B2} = \theta_B + \frac{\Delta\theta}{2} . \quad (5)$$

It must be noted here that although the scattered beam emerges in the right direction, the incident angle is still not at the exact Bragg incidence relative to the corrected frequency. Therefore, it is expected that the scattered efficiency upon restoration will not match the original ideal Bragg efficiency. As can be seen, the deviation between the incident angle and the current Bragg becomes half the original deviation $\Delta\theta$.

It can be shown that if the beam continues to move away from the ideal Bragg direction, restoration will increase the diffraction efficiency but since the incidence angle is not Bragg matched, the ideal diffraction efficiency may not be recovered by angular restoration. There is one exception to this general trend, however. For a current Bragg angle, say θ_{B2} , if the incident light beam moves closer to θ_{B2} relative to the current incidence angle, the diffraction efficiency will improve to a value higher than that after the preceding restoration. Following the new restoration, even though the output beam is stabilized, the actual diffraction efficiency will likely decrease compared to the preresoration value in this case. Hence, the diffraction efficiency after correction will be greater than that before correction only if the incidence angle moves *away* from the preceding Bragg. But our purpose here is not maximization of diffraction efficiency but stabilization of beam direction. Moreover, it can be shown that the loss of efficiency is not severe as long as near-Bragg is satisfied.

Note that any deviation from the current incident angle will result in a deviation from the correct scattered direction (S2 in the figures shown). But the diffraction formula measures the deviation from the current Bragg and not the deviation from the preceding incidence angle for which the output was stabilized. The two deviations, however, are simply related.

Starting with the same formula for the equivalent Bragg angle after restoration,

$$2\theta_{B,\text{after}} = \theta_{\text{inc}} + \theta_B ,$$

we now express θ_{inc} in terms of the current (pre-restoration) Bragg (which may not be θ_B) angle and deviations from it.

If the current Bragg (pre-restoration) angle is denoted by $\theta_{B,\text{before}}$, we then have

$$\theta_{\text{inc}} = \theta_{B,\text{before}} \pm \Delta\theta_{B,\text{before}} .$$

The deviation $\Delta\theta_{B,\text{before}}$ is measured using the photo-detector and the feedback algorithm. The \pm ambiguity arises because the diffraction efficiency formula is symmetric w.r.t. positive and negative deviations about the pre-restoration Bragg angle. The method to resolve this ambiguity is highlighted in the details of the algorithm discussed below.

2.1 Sequence of steps for the algorithm:

1. Determine the magnitude of the angular deviation ($\Delta\theta_{B,\text{before}}$) through the photo-detector output and the efficiency formula (implemented through table of pre-computed values)

This step is carried out using eq. (3) after scaling and normalizing the output from the interface to the photo-detector.

2. Determine whether it is a positive or negative deviation from $\theta_{B,\text{before}}$.

Steps involved in discriminating between positive and negative deviations are explained later.

3. Determine the new Bragg angle to restore the output direction of scattered light

$$2\theta_{B,\text{after}} = \theta_{B,\text{before}} \pm \Delta\theta_{B,\text{before}} + \theta_B .$$

4. Determine the frequency which will change the Bragg angle

$$f_{\text{new}} = \frac{2v_s \theta_{B,\text{after}}}{\lambda} \quad (6)$$

This frequency corresponds to an updated, equivalent Bragg angle that preserves the output beam direction.

5. Update variables such as Q , $\theta_{B,\text{before}}$, and the table of expected efficiencies as:

$$Q = \frac{L 2\pi \lambda f_{\text{new}}^2}{v_s^2}, \quad (7)$$

$$\theta_{B,\text{before}} = \theta_{B,\text{after}}$$

The table of expected efficiencies is recomputed using eq. (3) and the new values for the variables.

6. Send data to the output interface controlling the RF driver

The actual RF control may be achieved via either a voltage-controlled oscillator type frequency discriminating device, or by an equivalent digital-to-analog module.

Regarding discrimination between positive and negative deviation angles, the following strategy is adopted: Assume that the deviation is in the positive (moving away from the horizontal in a clockwise direction). Follow steps 3 (with the positive sign) and 4 and arrive at the frequency that would correct the light beam direction if the deviation were in the direction assumed. Then temporarily calculate the efficiencies for the two incidence angles, $\theta_{B,\text{before}} + \Delta\theta_{B,\text{before}}$, and $\theta_{B,\text{before}} - \Delta\theta_{B,\text{before}}$ (corresponding only to the calculated frequency correction for the positive deviation case). Send the information to the controller and compare the received intensity against the two values mentioned above and choose the deviation angle for which the intensity is closest to the observed value. At this stage, both the magnitude and direction of the angular deviation are known. The two efficiencies are expected to be different (when the frequency correction corresponds to only one sign) due to the asymmetry inherent in this process. If the right assumption for the deviation and frequency change have been made already, proceed directly to step 5 above.

2.2 Some numerical results

The parameters of the simulation based on the algorithm:

Center frequency corresponding to original Bragg = 40 MHz; length of Bragg cell = 5mm; velocity of sound in the medium = 2000 m/sec; light wavelength in the medium = 1 μm ; ideal/nominal Bragg angle = .01 radian; maximum deviation allowed within near-Bragg range = 20% of the ideal Bragg angle; resolution of the detecting and the frequency controller is 2^5 levels.

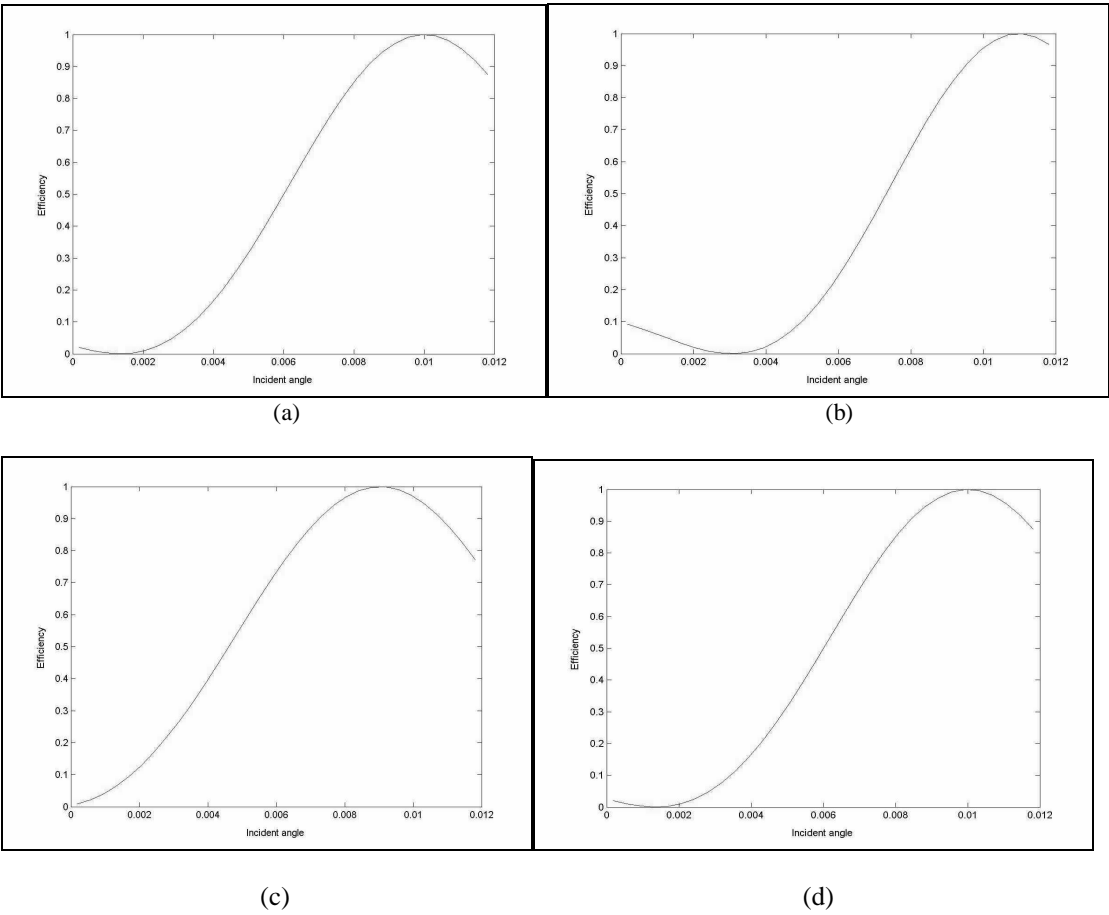
Table 1 shows the results obtained by running the angular correction algorithm with the parameters chosen above. The table lists the various incident angles, including the ideal Bragg (.01 rad) and deviations from it, both positive and negative. It also indicates the measured intensity (\propto efficiency) at the photodetector; the estimated incident angle; the required (new) Bragg angle and the required frequency adjustment. Following angular restoration, the expected restored efficiency and the value of the actual restored “output” angle are also listed. It is clear that in all the cases, the restored output angle is close to .01 radians, i.e., the ideal Bragg direction for the holographic grating, which was the main objective. It is also clear that even after restoration, the incident angle is close to the (current) Bragg angle, but never perfectly Bragg matched. It can also be seen that after restoration, the efficiency is generally significantly improved (specifically for cases where the subsequent angular changes do not bring the light beam closer to the Bragg angle following the preceding restoration, as was discussed earlier); it is, however, never 100% unless the incident angle is at

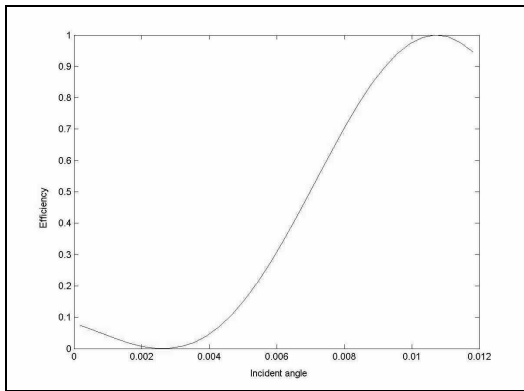
the original/ideal Bragg angle. One can also notice that once the incident angle comes back to the original Bragg angle, all parameters after restoration are the same as the operating parameters (the RF frequency is 40 MHz).

Table 1. Simulation results for correction of positive and negative READ angular deviations.

Incident angle (in radians)	Measured Efficiency	Detected angle (in radians)	New Bragg angle (in radians)	New frequency (in Hertz)	Restored Efficiency	Restored angle (in radians)
.012	.849508	.011937	.010969	43874999	.955610	.009937
.008	.639352	.008063	.009031	36124999	.969739	.010062
.01	.969739	.01	.01	39999999	1	.01
.0115	.913050	.011438	.010719	42874999	.976474	.009937

The series of graphs shown in Fig.4 (a-e) indicate the post-restoration diffraction efficiencies corresponding to the four off-Bragg incident angles described in Table 1. Note that the case in Fig.4 (a) represents the ideal case without





(e)

Fig.4. Graphs illustrating post-restoration diffraction efficiencies corresponding to incident angles (a) nominal/ideal Bragg; = .01 rad; (b) positive off-Bragg, .012 rad; (c) negative off-Bragg, .008 rad; (d) return to ideal Bragg; .01 rad; (e) positive off-Bragg; .0115 rad.

restoration. From the figures, we first note that the peak efficiency in each figure corresponds to the Bragg angle after restoration for each incident angle. Thus, for the ideal, non-deviated case, shown in Fig.4 (a), this peak has the value, ideally, of 100%, and occurs at .01 rad, the nominal Bragg angle. For the remaining off-Bragg incidences, we find that the resulting $\theta_{B,after}$ values are relatively close to the incidence angles, but of course, do not coincide. Also, note that the restored efficiency at the off-Bragg incidences is over 95% for the cases examined; these results graphically illustrate the data in Table 1. As a special note, we must mention that when the deviant incident angle returns to the nominal Bragg direction, the entire system restores itself to the perfectly ideal case. Note also that since the actual intensity received by the photodetector (which is essential for carrying out step 2 of the algorithm) cannot be measured in a numerical simulation, an alternative strategy is invoked to generate the results presented above. Details of the above procedures and others involving resolution and tolerances vis-à-vis the A/D electronic devices in the feedback loop are discussed in ref. [13].

2.3 Important assumptions for feedback correction algorithm:

- (i) $Q \gg 2\pi$ (to ensure near-Bragg operation);
- (ii) The beam profile can be ignored for our purposes and the light beam modeled as a ray;
- (iii) The photodetector is large enough that it captures the total intensity of the light beam;
- (iv) A deviation in only one plane has been assumed. But this could be extended to deviation in both vertical and horizontal planes by having a series of two Bragg cells that operate in orthogonal planes.
- (v) The source of beam deviation is at the input to the A-O/holographic setup, so that following angular stabilization, no further deviations occur.
- (vi) The rate of change of the input incidence angle is much slower than the overall response time of the feedback system.

3. EXTENSIONS TO INCORPORATE WAVELENGTH MISMATCH

Acousto-optic Bragg cells have been compared to holographic gratings from the perspective of linear coupled systems. Both may be analyzed using coupled wave theory, and extensions involving non-uniform beam profiles may be described by means of a transfer function approach. But there are some differences. In an acousto-optic Bragg cell, the Raman-Nath or thin grating limit is more readily and dynamically attainable; for the holographic case, thick gratings are more commonly recorded and studied. Acousto-optic gratings are dynamic and caused by time-varying sound waves, while holographic gratings are formed by optical interference, and are inherently static in nature. The latter distinction also leads to the absence of Doppler frequency shifts in the holographic scattered orders, which are present in the A-O devices. The acousto-optic gratings tolerate a much lower deviation from the Bragg than the holographic gratings, simply because A-O Bragg angles are typically much smaller than those of holographic gratings under standard sound frequency and other parametric conditions. Thus valid comparisons between the two can often be made quite straightforwardly for large Q and small Bragg angles.

Interestingly, while a general dephasing factor involving both angular and wavelength deviations has been developed for holographic gratings (see [5]), the corresponding A-O models do not as a rule consider dephasing due to wavelength changes, even though some general treatment has been made earlier [14,15]. We therefore begin by deriving an equivalent A-O dephasing model which incorporates direct analogy with the corresponding holographic model along the lines of [6].

According to the coupled wave theory, the diffraction efficiency for a transmission hologram with unslanted fringes can be expressed as:

$$\eta = \frac{(v)^2 \sin^2(\sqrt{(\xi)^2 + (v)^2})}{\xi^2 + v^2} \quad , \quad (8)$$

where v is a phase delay factor, and ξ is a dimensionless dephasing factor taking into account both incidence angle wavelength deviations of the READ beam that reconstructs the object from the hologram. As pointed out in [6], eqs. (3) and (8) are similar in form. It can be seen that v in the holographic case corresponds to $(\alpha/2)$ in the acousto-optic case and ξ^2 in the holographic case corresponds to $(\delta Q/4)^2$ in the acousto-optic case.

Now, in the holographic case

$$\xi = \frac{\vartheta d}{2c_{mr}} \quad , \quad (9)$$

where ϑ (the dephasing factor) denotes the mismatch between the grating vectors due to *both incidence angular mismatch and wavelength deviation*, and is defined by

$$\vartheta = K \sin(\theta_{mr}) - \lambda_{ir} K^2 / (4\pi n) \quad , \quad (10)$$

where θ_{mr} is the angle of READ beam in the medium; λ_{ir} is the wavelength of the READ beam in air; K is the magnitude of the grating vector; and d is the grating thickness (or L in the A-O case). Also, c_{mr} denotes the direction cosine, $\cos(\theta_{mr})$, and n is the nominal refractive index of the medium.

Under purely READ wavelength deviations, the above dephasing terms can be expressed as

$$\vartheta = K(\sin(\theta_{mr}) - \sin(\theta_B)) = - \frac{\Delta\lambda}{\lambda_{mw}} K \sin(\theta_{mr}) \quad , \quad (11)$$

where $\Delta\lambda$ is the wavelength deviation, and θ_B is the Bragg angle corresponding to the deviated READ wavelength.

At this point, we need to point out that for a wavelength deviation, a simply intensity-based angular restoration at the end of the sound cell by itself will not restore the holographic output angle, since the optical wavelength for the hologram would still be off-Bragg. Therefore, a strategy needs to be worked out such that the feedback compensation takes into account the efficiency and output angular changes and deviations for *both* A-O cell and the hologram. Fortunately, some recent work has enabled evaluation of the output angular deviations in a holographic grating under both angular and wavelength mismatch [4,16]. However, complete analysis of the approach required for the angular restoration for this case is beyond the scope of this paper.

4. SOME RELATED WORK BASED ON A-O FEEDBACK AND POSSIBLE EXTENSIONS

In [12], Balakshy and Kazaryan have tried to incorporate feeding back the detected intensity to change the frequency of the RF driver, thus affecting the direction of the scattered beam (as opposed to changing the intensity of the beam which is commonly done to achieve bistability and other effects). In their work, the direction of the beam is stabilized through frequency feedback. Their goals at the outset seem similar to those outlined in this paper. Their schematic setup is similar to the one outlined in this paper except for one major difference. They use a *transparency* which is crucial to

achieving stability. Thus, it is a transmittance-based stabilization scheme, while the scheme outlined in this paper is algorithmic using a computer / microprocessor-based approach. The transparency is the key element in their method; moreover, the dynamic range for their work is also limited to the relatively small A-O Bragg angles (milliradians). In the scheme outlined in this paper on the other hand, the AO selectivity (efficiency) of the Bragg cell is the key element in determining the deviation from the Bragg and hence the key element in correcting direction.

Finally, note that the proposed scheme is useful for very small deviations, which may not be very practical for actual holographic interconnection scenarios. Since the A-O Bragg angle is very small (unless sound frequencies in the gigahertz level are used), and the amount of deviation from the Bragg within which the current analysis is valid is a small fraction of the Bragg angle, the dynamic range is severely limited. To extend the dynamic range and stabilize the beam for larger, more hologram-like deviations, a two-stage process can be followed whereby (i) when a large deviation, say in excess of 20% of the nominal Bragg angle, is detected, a stepper motor assembly *rotates* the Bragg cell until perfect or near-Bragg matching condition for the given incident angle is achieved; (ii) at this stage, by comparing the resulting output scattered direction with the desired direction (assuming this to be within the allowable A-O angular tolerance), once again a frequency feedback strategy can be incorporated in order to restore the output light.

The above would be a two-step process, of which the first may be regarded as a coarse or macroscopic step, followed by a more precise or microscopic step.

The ideas outlined in this paper can be applied in a more general context to control the direction of a laser beam non-mechanically before it reaches the target when the source vibrates in space assuming that the frequency of the vibration of the source is much slower than the response time of the Bragg cell.

4. ACKNOWLEDGMENTS

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6. REFERENCES

1. J.Chrostowski and C.Delisle, "Bistable optical switching based on Bragg Diffraction," *Opt. Comm.* 41(3), pp. 71-74, 1982.
2. M.R. Chatterjee and J.-J. Huang, "Demonstration of acousto-optic bistability and chaos by direct nonlinear circuit modeling," *Appl. Opt.* 31(14), pp. 2506-2517, 1992.
3. S.-T.Chen and M.R.Chatterjee, "A Dual-Input Hybrid Acousto-Optic Set-Reset Flip-Flop and Its Nonlinear Dynamics," *Appl. Opt.* 36(14), pp. 3147-3154, 1997.
4. S.T.Chen, Ph.D Dissertation, Binghamton University (1997).
5. H. Kogelnik, "Coupled wave theory for thick hologram gratings," *Bell Syst. Tech.J.* 48, pp. 2909-2947, 1969.
6. M.R. Chatterjee and D.D. Reagan, "Examination of beam propagation in misaligned holographic gratings and comparison with the acousto-optic transfer function model for profiled beams," *Opt. Eng.* 38(7), pp. 1113-1121, 1999.
7. S. Min and M.R. Chatterjee, "General Integral Formalism for Acousto-Optic and Holographic Bragg Scattering for Arbitrary Profiles and Orientations," *Acustica* 77(3), pp. 118-128, 1992.
8. D.D. Reagan, M.S. Thesis, Binghamton University (1999).
9. M.R. Chatterjee and V. Ray, "Experimental investigations of wavelength and angular errors in holographic gratings with non-Bragg-matched READ beams," *SPIE Proc.* 3491, pp. 835-841 (1998).
10. M.R. Chatterjee, T.C Poon and D.N Sitter, Jr, "Transfer function formalism for strong acousto-optic Bragg diffraction of light beams with arbitrary profiles," *Acustica* 71, pp. 81-92, 1990.
11. A. Korpel, *Acousto-Optics*, Marcel-Dekker, New York, 1995.
12. V.I. Balakshy and A.V. Kazaryan, "Laser beam direction stabilization by means of Bragg diffraction," *Opt. Eng.* 38(7), pp. 1154-1159, 1999.
13. S. Ramchandran, M.S. Thesis, Binghamton University, 2001.
14. M.G. Moharam, T.K. Gaylord, and R. Magnusson, "Criteria for Bragg regime diffraction by phase gratings," *Opt. Comm.* 32, pp. 14-19, 1980.

15. M.G. Moharam, T.K. Gaylord, and R. Magnusson, "Criteria for Raman-Nath regime diffraction by phase gratings," *Opt. Comm.* 32, pp. 19-23, 1980.
16. M.R. Chatterjee, S. Min, and S.-T. Chen, "Geometrical analysis of the performance of holographic interconnection gratings with READ wavelength and angular perturbations using wavevector triads," under review.