ACOUSTO-OPTICS

TUTORIAL

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1.0 INTRODUCTION

The following tutorial will serve as an outline of the fundamental elements involved in the development of Acousto-Optic switching technology.

Acousto-Optic switching technology is based on the manipulation of light through the use of sound waves and a crystal. The benefits of such technology are numerous and include switching speed, energy efficiency, output capacity and negligible maintenance.

LMG has invented and developed four proprietary products, which are its Acousto-Optic (AO) Switch; its Multi-Channel AO Deflector; its Ultraviolet (UV) Scanner; and its Red-Green-Blue (RGB) Laser Projection System. Scientists at LMG's Research & Development facility are continually developing these products further.

2.0 THE ACOUSTO-OPTIC SWITCH

Currently, research is being conducted in the field of developing the acousto-optic crossbar switch [reference 1]. This switching idea is described in [refs. 1,2]. The essence of the idea is thus: in a 4×4 configuration optical switch, light is delivered to the switch by input ports (fibers) arranged in a linear array (4 fibers). Light from each input fiber is collimated along the optical axis. Each collimated beam is incident on one channel of a multi-channel acousto-optical cell (4 channels). The acoustic wave deflects off the incident light at an angle that is proportional to the addressing frequency. The radio frequency (*rf*) signal is tuned to provide the proper deflection angle. Light reaches the output fiber (one of 4 fibers) by passing through an optical system. The optical system then directs the beam from each vertical fiber position onto the horizontal output axis. It is point-to-point architecture where the *rf* signals are supplied to each channel by a single programmable *rf* source.

This approach provides a connection for each input fiber with each output fiber by means of a programmable *rf.* An advantage of this switch is the possibility of connecting several input channels (in this case 4) with the same number of output channels at the same time.

There is, however, a limitation with this switch. It is problematic to increase the quantity of input channels and output channels in this configuration. It is defined mostly by the configuration of the acousto-optic device and its optical scheme.

From our standpoint, the idea of using an acousto-optic cell for creating the switch (as in the case described above) is more attractive. The difference is that a collimated light beam is deflected on two co-ordinates by means of two acousto-optic cells. This approach has the same advantages as mentioned above, as well as having the ability to increase the quantity of output channels. This approach will now be considered.

3.0 PHYSICAL FUNDAMENTALS OF AN ACOUSTO-OPTIC CELL

An elastic-optical effect is a refraction index variation under a mechanical stress action. This effect is well known and described in many publications. In our description we follow [ref. 3]. The mechanical stress is created by means of an acoustic wave. The refraction index variation of the material occurs under the wave action. The refraction index value modulation is defined with the acoustic power supplied.

The photo-elastic phenomena are in all aggregate states of matter, including a crystal state at any crystal symmetry class (crystal lattice). The matter acquires the property of an optical phase grating for a period equal to the acoustic wavelength.

Acoustic wave propagating in an optical transparent substance causes a periodical variation of the refraction index n:

$$n(y,t) = n + \Delta n \sin(Ky - \Omega t)$$

The diffraction period grating is equal to:

$$\Lambda = 2\pi K^{-1}$$

where

Λ- is the ultrasonic wavelength.

If a light beam with aperture *a* much greater than Λ is coming through the substance, the diffraction pattern is created on output:

$$E(x,y,t) = E_0 \sum_{m=-\infty}^{\infty} C_m(x) \exp j[\omega_m t - (k_{mx}x + k_{my}y)n(y,t)],$$

where

$C_m(x)$ - is a relative wave amplitude of the mth maximum,

ω_m - is the wave frequency;

$$k_{mx}^2 + k_{my}^2 = k_m^2 = \omega_m^2 / c.$$

The amplitudes are described with a differential equation system:

$$2\frac{dC_m}{dx} = q_{m-1}C_{m-1}\exp(j\eta_{m-1}x) - q_{m+1}C_{m+1}\exp(-j\eta_m x) \qquad (1)$$

where

$$q_m = \Delta n k_m^2 / k_{m,x}\ ;\ \eta_m = (k_{m+1,x} - k_{m,x})n \qquad (2)$$

Also, the conditions are observed for any *m*:

$$\omega_{m+1} = \omega_m + \Omega;\ nk_{m+1,y} = nk_{m,y} + K \qquad (3)$$

Equation (3) defines the light wave frequency and its propagation direction for every maximum of diffraction. Usually, $\omega_m >> \Omega$, $k_m >> K$; thus the diffraction angles are small and Equation (2) looks like:

$$q_m \approx 2\pi\lambda^{-1}\Delta n = q\ ;$$

$$\eta_m \approx -2\pi\Lambda^{-1}[\theta_i + (m+1/2)\lambda / n\Lambda]\,,$$

where

θ_i - is the light wave incident angle on the plate x = 0,

λ - is the light wavelength in a vacuum.

The value Δn of light with a polarization vector d_α is associated with a stress amplitude *u* in the acoustic wave with equation:

$$\Delta n = 1/2n^3 b_{\alpha\alpha} u\,,$$

where

$b_{\alpha\alpha}$ are the indices determined from the analytical equations that describe a photo-elastic effect. The indices are the elements of the 4th rank elastic-optical tensor that associates the stress tensor components with the substance refraction index indicatrix. A kind of elastic optical tensor for all symmetrical classes of isotropic materials is presented in the reference literature. The kind of light diffraction on acoustic waves depends on the parameter:

$$Q = \lambda l / \Lambda^2 n,$$

There is the Raman-Nath diffraction of $Q \rightarrow 0$ with many diffraction maximums. There is the Bragg diffraction in the opposite case of $Q \rightarrow \infty$. With this condition, the light incident angle must be close to the Bragg angle θ_B:

$$\sin\theta_B = -\lambda f / 2nv = -\lambda / 2n\Lambda$$

where

v - is the acoustic wave velocity,

f - is the acoustic wave frequency.

At the Bragg diffraction, the pattern consists of two maximums: the first and second orders of the diffraction. The light intensity in the first order of the diffraction is defined with the equation:

$$I_1 = I_0 \frac{q^2}{q^2 + \eta_0^2} \sin^2\left(\frac{l}{2}\sqrt{q^2 + \eta_0^2}\right). \qquad (4)$$

If $\eta_0 = 0$, i.e. $\theta_i = \theta_B$, then Equation (4) may be transformed to:

$$. \; I_1 = I_0 \sin^2\left(\sqrt{\frac{\pi^2}{2\lambda^2} M_2 \frac{l}{l_1} P_{ac}}\right) \qquad (5)$$

where

$M_2 = b_{\alpha\alpha}^2 n_\alpha^6 / \rho v^3$ - is the acousto-optic quality of the substance;

ρ - is the substance density;

l and l_1 - are the ultrasonic beam cross-section dimensions;

P_{ac} - is the acoustic radiation power.

There is a possibility of diffracted light controlled by means of the acousto-optic power variation from the last expression. Equation (5) shows the modulation characteristics of the acoustic light amplitude modulator. A switching time is limited with sound propagation through a light beam aperture τ

$= a/v$. Because of the time required, the new acoustic wave amplitude size is established on all beam apertures.

As follows from this discussion, the acousto–optic cell is a unique element of the scanning light beam. According to Equation (3), the m^{th} diffraction maximum direction θm is defined with the equation:

$$\sin\theta_m = m\lambda / n\Lambda = m\lambda / nv\,.$$

The maximum diffraction is scanned after the angle at the ultrasound frequency variation. Usually, the first order of diffraction is used for scanning purposes. At the frequency variation in band Δf, the diffracted beam is deflected on an angle:

$$\Delta\theta_d = \lambda\Delta f / nv$$

The Bragg diffraction is used for scanning; however, it is selective. At the fixed incident angle θ_I, the diffraction occurs in the limited band Δf near the frequency

$$f_0 = 2nv\lambda^{-1}\sin\theta_i\,.$$

The band Δf may be calculated from Equation (4), assuming that the diffraction efficiency is small, i.e. $I_I/I_0 << 1$, thus, Equation (4) is changed to appear:

$$\frac{I_1}{I_0} = \frac{1}{4}q^2 l^2 \frac{\sin^2[(\pi l / \Lambda)(\theta_i - \theta_B)]}{[(\pi l / \Lambda)(\theta_i - \theta_B)]^2}\quad. \qquad (6)$$

The incident angle deviation tolerance at that intensity varies no more than 3 dB, equal to $|\theta_I - \theta_B| = 0.89\Lambda/\lambda$. Hence, the maximum scanning band is

$$\Delta f = 1.78nv^2 / \lambda l f_0\,.$$

The diffraction presented concerns the substance index refraction variation and describes only isotropy diffraction. There is another kind of diffraction in anisotropy materials that is related to the axes rotation of the light polarization in the substance under the acoustic wave action. This effect allows an increase in the scanning band. At the anisotropy diffraction, the light wave may be represented with Equation (1) in the interaction region. In this case, however, all even diffraction maximums have a polarization component that coincides with the incident wave polarization; all odd diffraction maximums have an orthogonal polarization.

Similarly, the isotropy diffraction frequencies of the wave are diffracted and satisfy the equation:

$$\omega_{m+1} = \omega_m + \Omega \,,$$

However, a propagation direction is different:

$$n_\alpha k_{m+1,y} = n_\beta k_{my} + K \,,.$$

where:

$\alpha, \beta = 1,2$ *u* $\alpha \neq \beta$.

The difference between n_1 and n_2 is small. However, this difference significantly changes the light and acoustic wave interaction geometry. The diffraction equations determining C_m coincide with Equation (1), where q_m and η_m may be found from the equation:

$$q_m = \frac{k_m^2}{k_{m,x}} \frac{n_1^2 n_2^2}{n_1 + n_2} b_{12} u \,; \;\; \eta_m = n_\beta k_{m+1,x} - n_\alpha k_m \,,$$

and b_{12} may be calculated from equations that describe the photo-elastic effect.

The incident angle θ_i and the diffraction angle θ_d may be determined by means of a wave vector diagram. It may be shown that:

$$\sin\theta_i = \frac{\lambda}{2n_i v}\left[f + \frac{v^2}{f\lambda^2}(n_i^2 - n_d^2) \right]$$

(7)

$$\sin\theta_d = \frac{\lambda}{2n_d v}\left[f - \frac{v^2}{f\lambda^2}(n_i^2 - n_d^2) \right] .$$

At the isotropy diffraction $n_i = n_d$, so Equation (7) is transferred, thus:

$$\sin\theta_i = \sin\theta_d = \lambda f / 2nv \,.$$

At the anisotropy diffraction $n_i \neq n_d$; commonly, $\theta_i \neq \theta_d$.

In reality, the interaction zone width l is always limited and the sound wave has a finite divergence. Because of this divergence, it is possible to define light scanning in the finite band as Δf.

At the isotropy, light diffraction on a sound wave with a divergence φs, the frequency deviation maximum Δf at the Bragg diffraction is observed; therefore, the scanning angle $\Delta\theta d$ and the resolution N are equal:

$$\Delta f = 2n\lambda_{-1}v\varphi s;\ \ \Delta\theta d = 2\varphi s;\ N = 2\varphi s/\varphi L.$$

For a uniform beam with a rectangular cross-section:

$$\varphi_s = 0.89\Lambda/l = 0.89v/lf.$$

The resolution at the Bragg anisotropy diffraction is inversely proportional to the ultrasound frequency. Hence, the resolution maximum may be achieved in a diffraction area between the Raman-Nath and Bragg diffractions.

At the anisotropy diffraction, the acousto-optic interaction geometry is possible with significantly more wide scanning bands being achieved. This means that $\Delta\theta d$ and N may be increased. This is caused by a different dependence of θ_i and θ_d against f, compared to the isotropy diffraction.

At a defined condition (near the incident angle minimum θ_i and an ultrasound wave propagation direction orthogonal to the optical axis of the one-axis crystal), a negligible acoustic beam divergence φs may provide scanning after the angle $\Delta\theta d >> \varphi s$. The dependence between the scanning angle and the ultrasound width at the anisotropy diffraction looks like:

$$\Delta\theta_d \approx 2.7\sqrt{\lambda / nl}\ .$$

The resolution advantage at the anisotropy diffraction compared to the isotropy diffraction is equal to:

$$N_{an} / N_{is} = 1.5 f_0 \sqrt{\lambda l / nv^2}\ .$$

The advantage is that the higher the ultrasound frequency, the longer the interaction zone.

Deflector resolution also depends on input light beam aperture *a*. This value is determined with a system rate. If a high scanning speed is not required, this value depends on optical matter quality and the ultrasound attenuation. The attenuation causes the diffracted light intensity to decrease and the light divergence to increase. The higher the ultrasound frequency, the more light divergence. This is because the absorption index is usually proportional to f^2. The absorption tolerance is near 4 dB at the aperture length.

Deflectors may carry out light beam scanning according to any rule. The minimum switching time that is necessary for the beam to switch from one position to another is $\tau = a/v$. Thus, the deflector is capable of scanning $(B = \tau^{-1})$ elements in a random scanning mode. However, at the linear ultrasound frequency variation, a higher scanning rate may be achieved. The advantage is achieved at the expense of random mode scanning loss, and in this case, the scanning mode is linear. At the linear scanning mode, the light beam switches to the next position for a time:

$$t_0 = (\sigma\tau)^{-1} ,$$

where

$\sigma = \Delta f / T$ -is the ultrasound frequency rate variation;

T - is the frequency period modulation.

The size of t_0 is $\sigma\tau^2$ less than time τ. A one-time scanning string is equal to T, and the less time the light scans at linear mode, the faster scanning occurs. However, after every discrete frequency jump there is a transitional process that has time τ in the system; thus scanning is accomplished within part of the frequency period only. The maximum quantity of pixels that are scanned per unit of time is achieved at $T = 2\tau$ and is equal to $B_{max} = \Delta f/4$. It is $N/4$ times more than in the same deflector with an arbitrary scanning mode.

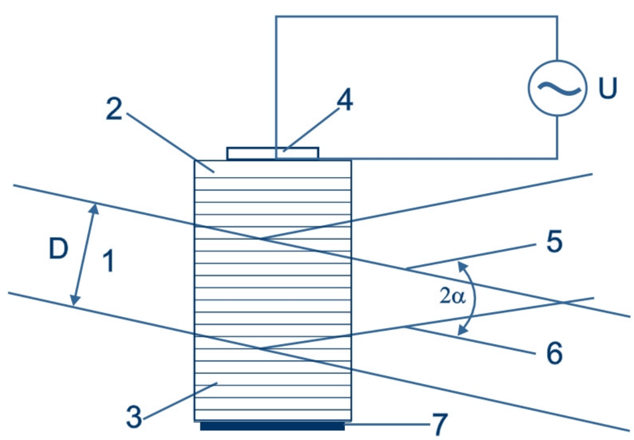
The main requirement of the crystal matter is the crystal's capability to create a regular structure of the variable refraction index. For this reason, the most important characteristics of the matter are the quality, *M2*, and the ultrasound attenuation. The grating created in the crystal provides: much larger deflection angles; a wider band of refraction index variations; and a wider ultrasound frequency band permitted by a crystal (and much better crystal quality). Also, an attribute of crystal quality is the tolerance to high density of input power radiation during a long period.

The reliability of an acousto-optic device can be investigated here; initially, with regard to scanners assigned for high-power laser radiation control.

The acousto-optic substance most attractive is paratellurit (TeO_2). The highest value of *M2* may be achieved thanks to the low speed of the transverse ultrasound waves. However, the absorption index is significant at the frequency 100 MHz, at 3 dB/sm. Therefore, another cut of crystal with a longitudinal acoustic wave on the "z" axis is preferable.

The basic scheme of the acousto-optic device will now be considered (shown in **Figure 1**). Usually, a crystal is used as the basic element of an acousto-optic device such as the deflector, scanner and switch. The crystal matter is optimally selected and processed for a required radiation wavelength (ultraviolet, visible or infrared band). The physics of a light beam and an acoustic wave interaction have been described above.

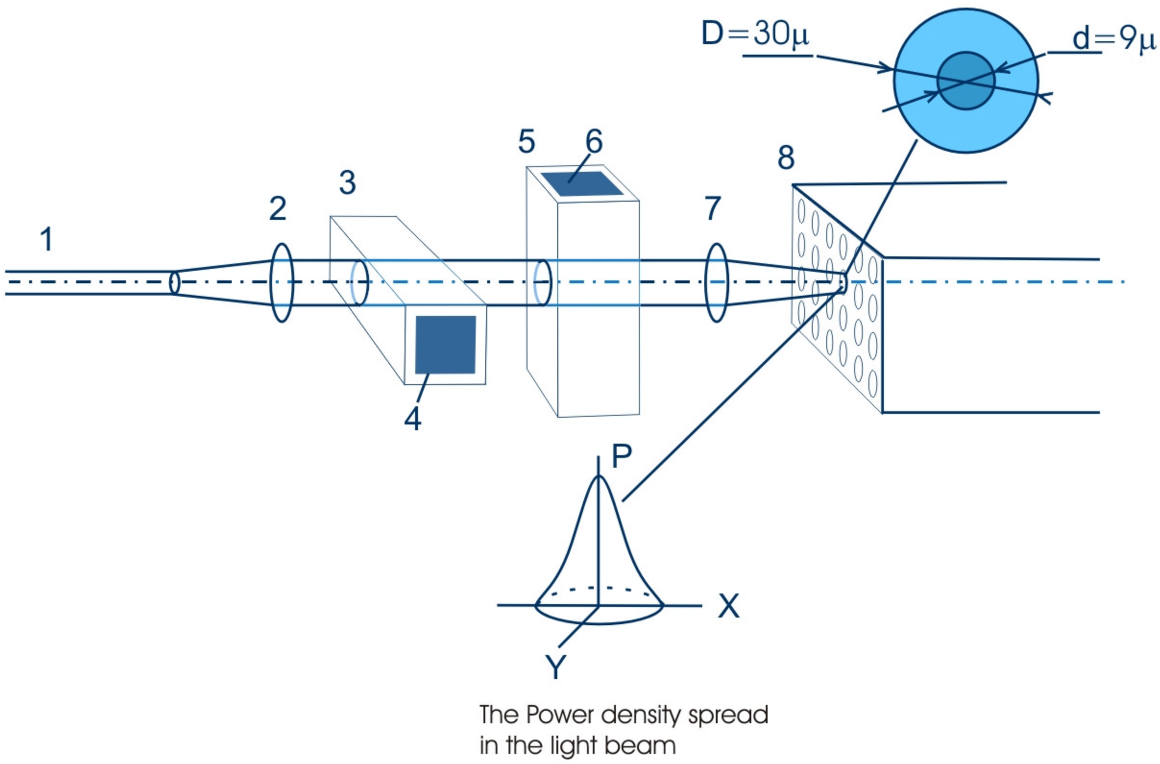
Ultrasound is injected into the crystal by means of a special element (transducer) fixed on the crystal surface. The role of the transducer is to transform a periodical electrical signal (radio frequency signal – rf) into a sound signal. The sound absorber is fixed on the opposite surface of the crystal to avoid interference from the reflection of a sound wave. This basic idea allows us to design devices that use collimated light beam control such as switches and scanners.



1 - input beam; **2** - acousto-optic crystal; **3** - regular structure created with ultrasonic wave; **4** - transducer; **5** - deflected beam; **6** - output beam passed without transformation (zero order); **7** - ultrasound absorber

Figure 1.

In the switch used for fiber optic applications, optical signals are redirected from one or several input fibers into another output fiber. The output fibers are usually joined in a bundle. In general, the switch uses the optical connection of input and output fibers that are controlled by a special program that controls the switching of the light beam. The scanner uses a scanning light beam in the same manner.



1 - fiber; **2** - input forming optical system; **3** - 1st AO crystal (x-dimension); **4**,6 - transducers; **5** - 2nd AO crystal (y-dimension) **7** - output forming optical system; **8** - output matrix of the fibers

Figure 2.

Figure 2 shows a configuration of the acousto-optic device that can be a basic design for a switch or a scanner. In the scanner, instead of the output bundle (8), a target may be used and an optical receiving channel may be added for analyzing a target pattern.

The important characteristic of the switch is the parameter that defines the optical losses. If the device is optimally designed and adjusted, these losses are due to reflection losses and losses at the light beam injection into an output fiber. The discrepancies between the light beam and the output fiber apertures cause the losses. Our research with the switch prototype shows reflection losses of 4 dB. The losses attributed to the light beam injection into an output fiber cannot be decreased to less than 1.5 dB using this prototype

4.0 APPLICATIONS OF THE ACOUSTO-OPTIC DEVICE

There are significant requirements arising in information exchange in recent years. Based on these needs, the rate and volume of transmitting data have increased significantly. Fiber optic systems now play a significant role in fulfilling these needs. Re-direction of the data stream is the most important problem that must be solved when developing the fiber optic system for data transmission. Opto-electronic and optical switches may be used as the apparatae that allow re-direction of the optical data stream.

Among the many types of optical switches, the acousto-optical switch is preferable on several parameters. Such advantages include its switching time and the ability to design the device with 1,000 outputs and more than one input. These switches may be applied to telecommunications and computer networks.

As previously mentioned, the basic configuration in Figure 2 is the basis for the scanner designed as visible at the UV band. Scanners of this kind are used in the fields of printing and designing, as well as surface inspection including microchips and printed plates.

UV scanners can be used for many diverse applications. An apparatus of this kind may be applied in areas such as photolithography, biotechnology, microscopy, micromachining and nanotechnology using laser beam control. Application of UV lasers in photolithography is due to the developing aspiration of increasing the microchip degree integration.

The analysis conducted shows that improving the photolithography apparatus follows these main directions: improvement of project optical systems in the field of image quality; increasing the numerical aperture; application of new substances, etc.; development of UV lasers and applications with a shorter wavelength and accompanying optic development; and development of systems with non-axis optics.

There are other directions that involve increasing the quantity of processed surfaces.

As the analysis shows, the scanner may be applied to beam scanning in an optical projection system instead of complicated optical mechanical equipment of the beam forming. However, the scanner must provide: the required accuracy of beam positioning (30-50 nm); the necessary beam size and the power density spread after a cross-section (uniformity is desirable); and the sample square (required covered) and the exposition required in every point of the sample. At the same time, the scanner must provide the system output (no more than 46 surfaces processed per hour – a minimum provided by existing systems).

The next area for application of the UV scanner concerns the different materials surface processing including glass, quartz and different kinds of polymers used for medical purposes. Usually with all technologies including microdrilling, the approach is similar to photolithography, (i.e. the application of different kinds of forming optical systems called "beam delivering" which masks the patterns that form on the surface). The processing of deep sets by the exposition and a pattern configuration are the results of changing masks. This operation is executed by computer control. Clearly these technologies are complicated and expensive; use of the UV scanner could make them much more affordable.

5.0 CONCLUSION

The study of optical switches shows that there are a number of switches, each one based on different fundamentals of physics. The most advanced direction is a switch based on micro-mirrors. However, this kind of switch has limitations caused by using mechanical parts. With the exception of the acousto-optical switch, most switches are in the initial stages of development and their parameters are much worse, (i.e. either poor switching speed or the small number of input/output channels).

Acousto-optical switches are all-optical and have several advantages that include:

- No moving mechanical parts
- Fluent electronic control
- High switching speed
- Reliability
- Small optical losses
- Many input channels and output channels

6.0 REFERENCES

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