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Acousto-Optic Deflector-Principles, Working and Applications

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ABSTRACT

Acoustic optic deflectors (AOD) have gained a lot of popularity as a fast way to scan the laser beam in optical coherence systems. It produces an acoustic wave that deflects the laser beam in a single direction. There are many factors to consider when choosing different solutions for acousto-optic spectral systems, but no comprehensive analysis or summary of these factors exists. In addition to summarizing the most popular optical schemes for acousto-optic spectral systems, this paper explains the basic principles of acousto-optic devices. A simulation study has also been performed to represent the characteristics of AOD in a practical environment. Additionally, applications of acousto-optic spectral systems in a few common fields are presented.

KEYWORDS: AOD, Bragg angle, Optical coherence tomography, RF frequency, Resolution.

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1. Introduction

The rapid rise of communication technologies with massive information transmission requirements can be attributed to the development of modern society such as, laser displays, optical inspection, signal processing and data storage. Until recently, the use of electromechanical devices was the most common way of laser beam deflection. The drawbacks of the electromechanical devices are associated with their system inertness, which limits their speed (4 μs for a mirror up to 10 mm in diameter). Electro-optic devices are fast, with a response time of the order of 10 ns, but their angular scanning range is limited to units of angular minutes, while their power consumption is very high. Non-mechanical inertia-free scanning based on the acousto-optic effect offers a more promising way. Acousto-optic deflectors (AODs) cover a range of scanning angles as wide as several degrees, their response time ranges from units to dozens of microseconds, so they are slower than electro-optical devices, but faster than mechanical systems [1],[2].

Essentially, such type of device (AOD) is operated with an electrical drive signal of constant power but a variable frequency. AO devices enable high-speed modulation, deflection, splitting, filtering, and focusing of light. These features, combined with their ease of implementation, have rendered them essential components of advanced optical microscopes, imaging, signal processing [3], [4], [5], [6].

We present an overview of AOD systems and their uses in optical coherence tomography in this review. Firstly, we outline the characteristics and working principles of AOD devices, highlighting their distinctions from one another. We then review recent advances in advanced interferometry systems, which use AOD devices as key components to enable their operation. In conclusion, we explore how AOD devices can contribute to the ongoing development of optical interferometry, both now and in the future.

2. Acousto optic deflector – working and principles

AOD is a device that is used for scanning the beam at high speed in one direction. Since it has no mechanical parts, it provides constant power and high signal-to-noise ratio at output. It is used for the electronic control of the intensity and position of the laser beam. When light interacts with the acoustic wave inside the deflector, a sinusoidal grating is generated in the medium. An incident laser beam passing through this grating will be diffracted into several orders. With proper adjustment of the incident angle between the laser light and the axis of acoustic propagation, the first-order beam can be made to have the highest efficiency.

A typical AOD consists of an RF driver, a signal generator, and an acoustic crystal. RF drivers provide constant power but variable frequency. Usually, RF driver contains a voltage-controlled oscillator, the frequency of which can be adjusted with an analog input drive signal. For achieving a nearly constant diffraction efficiency over a large frequency range, we need to increase the drive power for the extreme frequencies.

A key element of such a device is the transducer which converts electrical energy to acoustic energy. The acoustic frequency f is directly controlled by the DC voltage of the signal generator. Then the acoustic wave generated by the transducer induces rarefaction and compression in the crystal, leading to the change of refractive index through the crystal. Consequently, when the incident laser beam interacts with the acoustic wave generated by the transducer it deflects from its path into several spots at the outside of AOD.

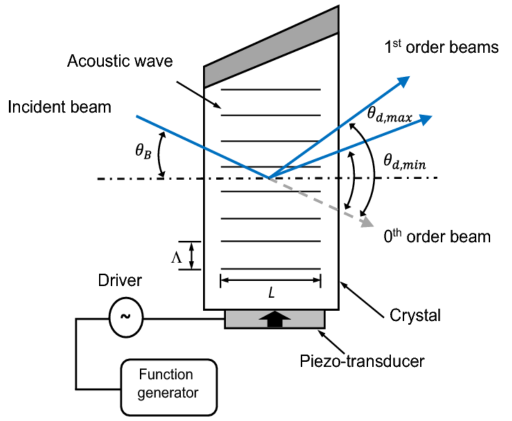

Fig.1: Schematic of the Acousto optic deflector system with the laser deflection.

When the AOD is operated in the Bragg regime, the interaction length L that the laser travels through the crystal must satisfy

$$L \gg \Lambda^2/\lambda \dots\dots\dots\dots\dots (1)$$

where Λ denotes the acoustic wavelength and λ is the wavelength of the incident laser. The maximum intensity of the first diffraction order is then located at a particular incident angle $\theta_i = \theta_B$, where θ_B is the Bragg angle that is a function of the acoustic frequency (f) and acoustic velocity (v) in the crystal as expressed in equation (2),

$$\theta_B \approx \sin\theta_B = \lambda f/_{2v} \dots\dots\dots\dots\dots\dots\dots (2)$$

The separation angle or deflection angles is twice the Bragg angle namely,

$$\theta_{sep} \approx \lambda f/_{v} \dots\dots\dots (3)$$

The maximum angular scanning angle of AOD is:

$$\theta_{scan} = \frac{\lambda\Delta f}{V} \dots\dots\dots (4)$$

where λ be the optical wavelength, Δf be the frequency bandwidth and V be the acoustic velocity.

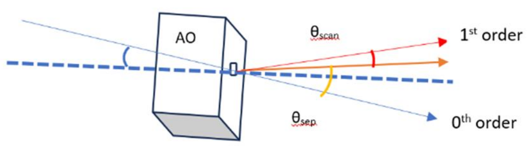

Fig.2: Laser deflector using the acousto- optic effect.

The fundamental idea behind acousto-optic deflectors is straightforward: the phase-matching condition, which can be adjusted by changing the value of the acoustic wave's propagation constant K, determines the acousto-optic deflection angle,

$$\theta_{def} = \theta_d - \theta_i \dots\dots\dots (5)$$

which has an absolute value of $2\theta_B$ in the case of nonbirefringent Bragg diffraction. Since $K = 2\pi f/v_a$, changing the acoustic frequency will change the deflection angle.

3. Performance Figures of AOD

3.1 Angular Scanning Range

The angular range of the diffracted output beam is limited by the applicable range of the acoustic frequencies (= drive frequencies), and it is inversely proportional to the sound velocity in the material. Usually, the usable range of deflection angles is rather small - a few degrees. This is because the usable acoustic wavelength is far longer than the optical wavelength. However, the angular range can be much larger than the beam divergence.

The basic parameters of AO deflectors are diffraction efficiency and an angular light scanning range in which an intensification of one parameter leads to the deterioration of another. From equation (3), we can see that the wider the band of acoustic scanning frequencies, the larger the scanning angle. On the contrary, the wider the scanning angle, the lower the diffraction efficiency of the device averaged over this band.

Recently a method was proposed by S. N. Antonov where an additional deflector was used to fulfill the Bragg phase–matching condition over the entire scanning range of the main deflector. It has been established experimentally that the operating bandwidth of the device is 32 MHz for a diffraction coefficient of no less than 90%, which determines a light beam scanning angle of 50 mrad [7].

3.2 Resolution

The resolution of AOD is usually defined as the ratio of the range of scan angles of diffracted beam to the input beam divergence. Minimum beam divergence is achieved by maintaining the size of the input beam. That means AOD should not be operated with unnecessarily strong focusing of the input beam for high getting high resolution. A huge input beam may result in diffraction effects, which may harm the application.

3.3 Diffraction Efficiency and Response Time

The diffraction efficiency, which is usually in the range of 60%, is a crucial performance parameter. Achieving a high diffraction efficiency across a significant frequency range is preferable, not just at the ideal drive frequency. Various factors need to be considered to achieve high diffraction efficiency. For the initial setup, the input beam must be polarized, and it must fit into the aperture of the AOD

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device. Then we must confirm that the output beam of AOD is not being clipped. Finally, we need to adjust the AOD's Bragg angle to get high efficiency of 1st order.

One of the reasons of using AOD is its faster scanning time. That means its response time is quite higher than any other mechanical device.

The response time is written as

$$\tau = \frac{d}{v_a} \ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

where d be the active aperture and V_a be the acoustic velocity of the device.

3.4 Materials of AOD

Different materials are used for Acousto optic deflectors, such as crystal quartz, gallium phosphide, lithium niobate and tellurium oxide. Among them, tellurium oxide is now of interest for Q-switch and deflector [8]. Such crystals exhibit exceptionally high AO quality, transparency, and radiation stability at wavelengths of 0.35–5 μm [7].

Table 1: Typical figures for a range of interaction materials are listed below: [9]

Material	Acoustic Velocity	Figure of Merit	Refractive Index	Wavelength Range
Te02	4.2	34.5	2.26@0.633	NUV/VIS/NIR
PbMo04	3.63	36.3	2.38@0.633	VIS/NIR
Quartz	5.7	2.38	1.54@0.633	UV
Fused Silica-Long	5.96	1.51	1.46@0.633	UV/NIR

3.5 Applications of AOD

Applications where a laser beam needs to be steered very precisely and possibly quickly are common; some examples are.

- Photolithography
- Laser displays
- Optical Tweezers
- Beam-addressed optical memory
- Optical Inspection
- Signal processing

In recent times, non-destructive and non-invasive measurements to visualize the internal structure have achieved significant attention. To visualize the internal structures of the objects, high-speed and high-sensitivity wavelength scanning detectors are required. This feature has been demonstrated by using an external cavity diode laser. Littrow or Littman type with reflective diffraction grating was proposed. In addition to this, mechanically moved devices like the Galvano meter, and polygon mirror have also been proposed. The mechanics of these configurations reduce the reliability, linearity, and speed of wavelength scanning. To overcome these problems caused by mechanical movement, a non-mechanical device like AOD was proposed. And it was successfully possible to extend the tunable range and the tuning rate of scanning.

4. Research Progress of AOD on Optical Coherence Tomography

The function of AOD is to sweep the frequency of the laser beam by applying acoustic waves through the transducer into the medium. Frequency-swept laser based on AOD is a promising swept source in optical coherence tomography (OCT) applications for its high scanning speed without mechanical motion. The laser may tune over time due to its appropriate configuration and is favorable for fast imaging because it avoids data resampling and recalibration, as are required in conventional swept source optical coherence tomography (SS-OCT). High-speed imaging on the microsecond order and shadowgraph using a continuous wave laser was made possible using AOD [10], [11], [12], [13].

Takamasa Suzuki et al demonstrated a wide tunable range using a laser diode with an anti-reflection coating and an external cavity employing an Acousto optic deflector. A total scanning range of 15 nm and FWHM of 0.2 nm was proposed. A tuning rate of 100 KHz was achieved without any mode hops [14].

Tiancheng Huo., et al proposed a swept source laser based on AOD and a reflection grating. They achieved k-linearity with Pearson's r correlation coefficients of 0.99995 without and 0.99997 with optimization. The laser has a tuning range of 50 nm, a 3 dB swept range of 42 nm (FWHM), the output power of 2.56 mW, 6 dB sensitivity roll-off depth of 0.941 mm, and a central wavelength of 1064 nm at a scanning rate of ∼20 kHz. Scanning rate as high as ∼400 kHz was also achieved for this laser with the tuning range 49 nm, swept linearity of 0.99990, output power of 2.30 mW, and a 6 dB sensitivity roll-off depth of 0.550 mm [15].

Tiancheng Huo et al demonstrated ultra-high speed optical coherence tomography based on a swept source using an AOD of 40 MHz. The maximum output power of 41.2 mW, tuning range of 40 nm and a high scan linearity in wave number of 0.9996 was conformed. With sensitivity of 87 dB, high-speed OCT imaging of biological tissue in vivo was also demonstrated [16].

By using a confirmed external cavity system with a unique antireflection-coated laser diode operating at 770 nm, the tunable range could be increased. With no mechanical components, an acousto-optic deflector allowed for a

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tuning range and rate of 22 nm and 20 kHz, respectively [17].

M. H. Chen, Y. P. Fan, H.Zhang studied swept laser by using acous optic tunable filter. A semiconductor optical amplifier was used as a gain medium and the AOTF was used as a wavelength-selected element in the internal fiber ring cavity. With the SOA injection current of 280 mA, the continuous wavelength tuning range of the source was 1294-1368 nm centered at a wavelength of 1330 nm its sweep rate was 3.72 KHz, full-width half maximum is 51 nm and the output power was 1.14 mW [18].

Zhangwei Hu., He Bin., Yejiong Shi demonstrated a compact high-speed linear swept laser based on AOD using Doppler shift compensation, achieving a high linearity of Pearson's R of 0.999991. An extended coherence length of 5.7 mm, an output power of 18 mW, excellent phase stability at a sweep speed of 500 kHz, and OCT structural images with a system sensitivity of 103.2 dB were successfully performed [19].

It was finally shown how to create a novel external cavity laser diode without a diffraction grating. AOD was utilized as a grating and deflector in this arrangement. The suggested arrangement achieves a stable optical resonator with a constant cavity length, high-efficiency optical feedback, and a broad range of wavelength scanning with a straightforward configuration. About 60 nm and 50 kHz were the scanning range and, maximum frequency response respectively [20].

5. Simulation Results of Different AOD device

Based on the principle of AOD, here we compare different deflector design configurations and analyze their effect on scanning angle parameters and Rf frequency range. The reason of choosing these devices is their different acoustic velocity and center frequency. The specifications of these AOD devices are given below:

Table 2: Specifications of two AOD devices [21]

Configurations	AOD (1)	AOD (2)
Acoustic mode	Shear off axis	Shear off axis
Acoustic velocity	**660 m/s**	**710 m/s**
Center frequency	87 MHz	200 MHz
Aperture	8.5 mm	4.8 mm
Polarization	90^0	90^0
Material	TeO_2	TeO_2

Both configurations are optimized for consecutive scanning of visible laser beams. The following figure shows the comparison result of RF frequency range with incident wavelength for TeO_2 (660 m/s) with center frequency 87 MHz and TeO_2 (710 m/s) with center frequency 200 MHz.

The raising time or response time of both devices are calculated by using equation (6). The response time for device 1 is 12.87 µsec and for device 2 is 6.760 µsec. That means the response time for device 2 with higher acoustic velocity is higher than device 1 of lower acoustic velocity.

For measuring rf frequency, at first, the acoustic wavelength (Λ) is calculated by using Bragg equation for incident beam. Then incident angle (θ_i) in terms of operating wavelength (λ) is measured. After that the required rf frequency for this visible waveband is calculated and compared with AOD1 and AOD2. The comparison result between the devices is given below.

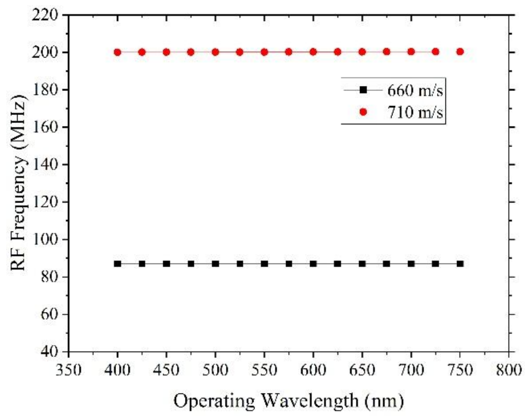

Fig.3: Comparison result of rf frequency vs incident wavelength for two acoustic devices.

From this figure, we see that the rf frequency is comparatively higher for higher acoustic velocity. Also, for higher rf frequency, the scanning angle will be higher. The graphical representation of this simulation is shown below.

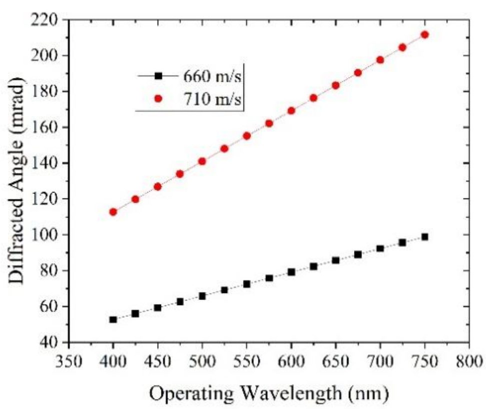

Fig.4: Comparison result of diffracted angle vs incident wavelength for two acoustic devices.

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From the above figure, it is also observed that for higher acoustic velocity, the scanning angle will be higher than the lower acoustic velocity of AOD device. Therefore, it is observed that higher acoustic devices provide higher rf frequency, higher diffracted angles, and lower response time. So, for practical applications of AODs, higher acoustic velocity will be more appropriate than lower acoustic velocity. This numerical model would be an important consideration for practical applications of AOD.

6. Conclusion

Non-contact measurement has become more and more in demand in the industrial world. Numerous approaches have already been put forth for non-contact external cavity diode laser system (ECDL). However, no single technique can successfully identify objects at a high rate of speed and resolution. The tuning range of these ECLDs was not sufficiently wide, and their scanning speed was significantly restricted. An acousto-optic technique that uses the interaction between sound and light waves is a great candidate for realizing fast and nonmechanical wavelength scans. It has been feasible to detect objects with high speed and resolution using AOD. The present simulation also shows that higher acoustic velocity implies higher rf frequency and higher scanning angle. That is important for scanning the light beam over a large angle. Also, it is easy to separate the diffracted beam from the zeroth order if the scanning angle is large. In the future, the consideration of AOD at high acoustic speed in OCT will be a milestone for all wavelength bands.

References

[1] A. W. Warner, D. L. White, W. A. Bonner, Acousto-optic light deflectors using optical activity in paratellurite, *Appl. Phys. Letters, 43(*11), 1972.

[2] X. Lei, Z. Shangian, et al, Electro-optical Analog-to-Digital Converter based on LinbO3 Mach-Zehnder Modulators, *The 9th International Conference on Optical Communication and Networks* – Nanjing, 2010, 343-346.

[3] A. M. Abd El-Naser, N. Z. R. Ahmed and S. F. Mohammed, Transmission Characteristics of Radio over Fiber (ROF) Millimeter Wave Systems in Local Area Optical Communication Networks, *International Journal of Advanced Networks and Applications, 26*, 2011, 876-886.

[4] T. Fukuchi, K. Nemoto, K. Matsumoto, K. Uchino, Application of an acousto-optic laser deflector to interferometric measurement of discharges in air, *IEEJ Trans FM, 124*, 2004, 56–61.

[5] P. Itay, k. Ron, and K. Zev, Acousto-optics bandwidth broadening in a Bragg cell based on arbitrary synthesized signal methods, J. *Applied Optics, 54*, 2015, 5065-5073.

[6] A. Coquin, J. P. Griffin, and L. K. Anderson, Wide-band Acousto optic deflectors using acoustic beam steering, *IEEE Trans. Sonics Ultrason, 17*, 1970, 34–40.

[7] S. N. Antonov, Acousto-Optic Deflector with a High Diffraction Efficiency and Wide Angular Scanning Range, *Acoustical Physics, 64(4)*, 2018, 432–436.

[8] W. A. Bonner, S. Singh, L. G. Van Uitert and A. W. Warner, High quality tellurium oxide for Acousto optic and nonlinear applications, *journal of electronic materials, 1*, 1972, 154-164.

[9] http://isomat.com/acousto_optics.html.

[10] H. W. Presley, L. M. Burberry, A. F. Abbenante, Acousto-optic deflector for free-space laser communications, *Proc. of SPIE*, *1950*, 05-114.

[11] F. Tetsuo, N. Takuya, N. Kosichi and U. Kichiro, Development of a High-Speed Laser Interferometer Using an Acousto-optic Deflector, *Electrical Engineering in Japan, 148(2)*, 2005, 1531-1536.

[12] F. Tetsuo, N. Koshichi, High-speed shadowgraphy and interferometry using an acousto-optic laser deflector, Proc. of SPIE, 5920, 2005, 59200R1-59200R10.

[13] F. TETSUO, N. KOSHICHI, M. KOUJI and H. YOSHIKI, Visualization of High-Speed Phenomena Using an Acousto-optic Laser Deflector, *Electrical Engineering I Japan, 154(3)*, 2006, 113-118.

[14] S. Takamasa, N. Ryu-ichi, S. Osami, C. Samuel, Rapid wavelength scanning based on acousto-optically tuned external-cavity laser diode, *Optics Communications*, *248*, 2011,4615-4618.

[15] H. Tiancheng, W. Chengming, et al, Ultrahigh-speed optical coherence tomography utilizing all-optical 40 MHz swept-source, *Journal of Biomedical Optics · 20(3)*, 2015, 0305031- 0305033.

[16] H. Tiancheng, Z. Jian, Z. Jing-gao, C. Tianyuan, Linear-in-wavenumber swept laser with an acousto-optic deflector for optical coherence tomography, *Opt. Lett. 39(2)*, 2, 2014, 247-250.

[17] S. Takamasa, A. Shingo and C. Samuel, Two-dimensional thickness measurement using an acousto-optically tuned external-cavity laser diode, *Proc. SPIE, 9628*, 2015, 96281K1- 96281K-8.

[18] M. H. Chen, Y. P. Fan, H. Zhang, Swept source laser by Acousto optic tuning, *Optics and Precision Engineering, 24(11)*, 2016, 2658-2664.

[19] H. Zhangwei, B.He, S. Yejiong, High-speed k-linear swept laser using acousto-optic deflector with Doppler shift compensation, *Opt. Lett, 49(1).*2023.

[20] S. Takamasa, K. Yuzuki, C. Samuel and S. Osami, External-cavity laser diode using acousto-optic deflector as tunable grating, *Opt. Lett. 47(7)*, 2022.

[21] https://gandh.com/products/acous-optics/deflectors.