Research Article

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Silicon-Germanium Dioxide and Aluminum Indium Gallium Arsenide-Based Acoustic Optic Modulators

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Abstract: The purpose of this study was to clarify the silicon-germanium dioxide (SiGeO₂) and Aluminum Indium Gallium Arsenide (AlInGaAs) based acoustic optic modulators for upgrading transmission performance characteristics. The transient time response of these modulators is analyzed and discussed in detail. The 3-dB modulation signal bandwidth, diffraction signal efficiency, signal rise time, and signal quality factor with minimum data error rates are also considered. The proposed models with silicon-germanium dioxide and Aluminum Indium Gallium Arsenide acoustic optic modulators were compared to the previous model with silicon acoustic optic modulators. The results confirmed the high-performance efficiency of the proposed models when compared to the previous model, in both the lowest transient time response and the highest acoustic optic modulators speed response.

Keywords: Modulation bandwidth, Acoustic modulators, silicon-germanium dioxide, and Aluminum Indium Gallium Arsenide

1 Introduction

Acoustic, optical devices are used in optical systems for light beam control and signal processing applications [1–4]. Acoustic optics has developed into a mature technology and is deployed in a wide range of optical system applications [5–9]. They are used in optical information processing, tunable optical filters, deflectors, broadband delay lines, mode-locked, acoustic optic sensors, and laser radiation modulators [10–13]. An acousto-optic modulator (AOM), also called a Bragg cell, uses sound waves to diffract the frequency of light. As with a permanent Bragg grating, the various wavelengths are spatially diffracted and separated from each other. When ultrasonic waves propagate on optical fibers, it causes periodic micro-bending of the optical fibers and a change in the refraction index of the fiber core. This bending is called the elastic-optic or acousto-optic effect. Although this basic theory of acousto-optic diffraction in isotropic media was well understood, there were relatively few practical applications before the invention of the laser [14–18]. It was the need for optical devices for laser beam control that stimulated extensive research on the theory and practice of acousto-optics. Over the years, the acousto-optic effect has been exploited for the development of dynamic and reconfigurable all-fiber devices. The use of flexural, longitudinal, or torsional elastic modes led to the development of tunable filters, frequency shifters, and switches [19]. Recently, the acousto-optic effect has also been used as a technique for the fine characterization of optical fibers [20–22], and the generation of cylindrical vector beams [23, 24]. In recent years, the development of superior acousto-optic materials and efficient broadband transducers are the primary contributors to significant progress in acousto-optic (AO) devices [25, 26].

Modulating an incoming laser light can be achieved with an AOM by varying the amplitude and frequency of acoustic waves traveling through the crystal [27]. Many characteristics, such as laser beam deflection, intensity modulation, phase modulation, and frequency shifting, can all be achieved using the AOM [27]. To describe this acousto-optic effect in crystals, a plane wave analysis can be used to determine the frequency and angular characteristics of the acousto-optic interaction [28–31]. In this approach, the acoustic wave is approximated as a single plane wave typically propagating to the transducer [17, 18, 32–35]. The frequency or angular dependence is obtained
from the phase mismatch caused by the change of acoustic frequency or incident optical wave direction [36–43].

2 Acoustic Optic Modulators Description with Equations Analysis

Figure 1 shows a basic schematic view of the acoustic optic modulators. The incident optical beam is assumed to be a plane wave propagating near the z-axis in the xz plane (referred to as the interaction plane).

To accommodate the finite size of the transducer, the acoustic beam is modeled as an angular spectrum of plane waves propagating near the x-axis. The AO diffraction only occurs in the interaction plane where the phase-matching condition is satisfied. The intensity and distribution of the diffracted light are proportional to the acoustic power spectra. The angle of diffraction is a function of the acoustic frequency, and acoustic velocity of the optical device is [14, 17, 18]:

$$\theta = \frac{\lambda f_a}{V_a}.$$  \hspace{1cm} (1)

$\theta$ is the incident beam laser and the diffracted laser beam. The diffraction efficiency is [14, 17, 28, 37, 38]:

$$\eta = \frac{\pi}{\lambda} \sqrt{\frac{M_2 P_o W}{2 H}},$$  \hspace{1cm} (2)

Where $P_o$ is the acousto power, $M_2$ is the figure of merit for the acoustic optic material, $W$ is the modulator width, $H$ is the modulator length or height. The light beam waist diameter is expressed by [5, 14, 17, 29, 39]:

$$d = \frac{1.27 F \lambda}{D},$$  \hspace{1cm} (3)

Where $F$ is the length of the focal lens, $D$ is the beam diameter of the laser, and $(\tau_r)$ is the acoustic optic modulator rise time [5, 14, 17, 40]:

$$\tau_r = \frac{0.66 d}{V_a}.$$  \hspace{1cm} (4)

The 3-dB frequency bandwidth is a function of the acoustic optic modulator rise time [5, 6, 14, 17, 30, 31, 41]:

$$f_{3-dB} = \frac{1}{2 \tau_r}.$$  \hspace{1cm} (5)

The signal modulation frequency of the acoustic optic modulators can be utilized as [5, 6, 14, 17, 32, 42]:

$$f_m = \frac{0.29 \sqrt{\alpha}}{\tau_r},$$  \hspace{1cm} (6)

Where $\alpha$ is the signal loss through the acoustic optic modulators. The modulator transfer function of the acoustic optic modulators can be modeled as the following [5, 6, 17, 33, 43]:

$$MTF = \exp\left(\frac{0.833 f_{m}}{f_m}\right),$$  \hspace{1cm} (7)

Where the SiGeO$_2$ acoustic optic modulator’s acoustic velocity value is $4.2 \times 10^6$ mm/sec, its loss value is 0.063 dB/GHz.mm, and its figure of merit value is $34.5 \times 10^{-15}$ m$^2$/W. While the AlInGaAs acoustic optic modulators velocity value is $6.32 \times 10^6$ mm/sec, its loss value is 0.038 dB/GHz.mm, and its figure of merit value is $44.8 \times 10^{-15}$ m$^2$/W. The contrast ratio is a function of both the transfer function and signal modulation frequency and is shown as [6, 14, 17, 34, 35]:

$$CR(f_m) = \frac{1 + MTF(f_m)}{1 - MTF(f_m)},$$  \hspace{1cm} (8)

$$CR_{dB} = 10 \log CR(f_m)$$  \hspace{1cm} (9)

Where the materials-based acoustic optic modulators can be expressed as the refractive index [6, 14, 17, 35]:

$$n = \frac{\sqrt{B_1 + B_2 \lambda^2}}{\lambda - B_3^2}$$  \hspace{1cm} (10)

Where the constants for the proposed SiGeO$_2$ and AlInGaAs AOMs are clarified based on Refs. [6, 7, 14, 17]. Where $B_1 = 0.6542$, $B_2 = 6.654 (T/T_0)$, $B_3 = 7.8765$ for SiGeO$_2$ AOM, $B_1 = 1.6543$, $B_2 = 0.2136 (T/T_0)$, and $B_3 = 3.6532$ for AlInGaAs AOM [6, 7, 14, 17]. The acoustic optic modulator Q-factor and its bit error rates are expressed as [5, 6, 14, 17]:

$$Q = \frac{2 \pi \lambda L}{n V_a}$$  \hspace{1cm} (11)

The higher the modulation speed, the smaller the transit time that can be achieved. So, the transient AOM time and the modulation speed are expressed as [14, 17, 36, 43]:

$$T_t = \frac{d}{V_a},$$  \hspace{1cm} (12)

$$MS = \frac{0.25}{T_t}$$  \hspace{1cm} (13)
3 Simulation Results and Discussions

The selection of AO materials depends on the specific device application. AlInGaAs is perhaps the best choice for making wideband AO modulators. High optical transparency over the wavelength range of interest is achievable in large single crystals properties that are specifically required for AO device applications. The transient time, modulator Q-factor, modulation contrast ratio, 3-dB frequency bandwidth, modulation frequency, and modulator performance are dependent on the variables defined in Table 1.

Table 1: Variables for the acoustic optic modulators

| Variables     | Variable Definition          | Values/units          |
|---------------|------------------------------|-----------------------|
| $T = T_0$     | Ambient temperature          | 300 K-450 K           |
| $\Lambda$     | Laser wavelength             | 1550 nm               |
| $f_a$         | Acoustic frequency           | 5 KHz                 |
| $F$           | Modulator focal length       | 10 mm                 |
| $D$           | diameter of laser beam       | 0.1 mm-0.5 mm         |
| $P_a$         | Acoustic power               | 100 mW                |
| $H$           | Height of modulator          | $H = 10$ mm           |
| $L$           | Length of interaction        | 0.35 mm               |
| $W$           | Width of the modulator       | 8 mm                  |

Figure 2 illustrates the variations in modulator rise time related to laser beam diameter for both previous and proposed AOMs at room temperature. The modulator rise time for AlInGaAs AOM is 12 ns with a 0.1 mm beam diameter, 9 ns with a 0.3 mm beam diameter, and 6 ns with a 0.5 mm beam diameter. The modulator rise time for SiGeO$_2$ AOM is 15 ns with a 0.1 mm beam diameter, 10.5 ns with a 0.3 mm diameter beam, and 6.565 ns with a 0.5 mm diamet-

ter beam. For the previous silicon AOM, the modulator rise time is 20 ns with a 0.1 mm beam diameter, 14 ns with a 0.3 mm beam diameter, and 8 ns with a 0.5 mm beam diamet-

ter.

Figure 3 shows the variations in modulator frequency response related to beam diameter for both the previous and proposed AOMs at room temperature. The modulator frequency response for AlInGaAs AOM is 3 GHz with a 0.1 mm beam diameter, 9.81 GHz with a 0.3 mm beam diameter, and 36 GHz with a 0.5 mm beam diameter. The modulator frequency response for SiGeO$_2$ AOM is 2 GHz with a beam diameter of 0.1 mm, 8 GHz with a 0.3 mm beam diameter, and 32 GHz with a 0.5 mm beam diameter. The modulator frequency response for the previous silicon AOM is 1.5 GHz with a 0.1 mm beam diameter, 6 GHz with a 0.3 mm beam diameter, and 24 GHz with a 0.5 mm beam diamet-

ter.

Figure 4 shows the variations in modulation frequency in relation to the laser beam diameter for both the previous and proposed AOMs at room temperature. The modulation frequency for AlInGaAs AOM is 6 GHz with a 0.1 mm beam diameter, 24 GHz with a 0.3 mm beam diamet-

Figure 2: Variations in modulator rise time in relation to laser beam diameter for the previous and the proposed AOMs at room temperature

Figure 3: Variations in modulator frequency response in relation to laser beam diameter for the previous and the proposed AOMs at room temperature

Figure 4: Variations in modulation frequency in relation to laser beam diameter for the previous and proposed AOMs at room temperature
Acoustic Optic Modulators

The modulation frequency for SiGeO$_2$ AOM is 5 GHz with a 0.1 mm beam diameter, 20 GHz with a 0.3 mm beam diameter, and 80 GHz with a 0.5 mm beam diameter. The modulation frequency for the previous silicon AOM is 4 GHz with a 0.1 mm beam diameter, 16 GHz with a 0.3 mm beam diameter, and 64 GHz with a 0.5 mm beam diameter.

Figure 5 shows the variations in modulator speed response in relation to the laser beam diameter for both the previous and proposed AOMs at room temperature. The modulator speed response for AlInGaAs AOM is 6.5 GHz with a 0.1 mm beam diameter, 25 GHz with a 0.3 mm beam diameter, and 97 GHz with a 0.5 mm beam diameter. The modulator speed response for SiGeO$_2$ AOM is 5.5 GHz with a 0.1 mm beam diameter, 21 GHz with a 0.3 mm beam diameter, and 82 GHz with a 0.5 mm beam diameter. The modulator speed response for the previous silicon AOM is 4.5 GHz with a 0.1 mm beam diameter, 18 GHz with a 0.3 mm beam diameter, and 66 GHz with a 0.5 mm beam diameter.

Figure 6 shows the variations in modulator transient time response in relation to the laser beam diameter for the previous and proposed AOMs at room temperature. The modulator transient time response for AlInGaAs AOM is 320 ns with a 0.1 mm beam diameter, 200 ns with a 0.3 mm beam diameter, and 75 ns with a 0.5 mm beam diameter. The modulator transient time response for SiGeO$_2$ AOM is 350 ns with a 0.1 mm beam diameter, 250 ns with a 0.3 mm beam diameter, and 120 ns with a 0.5 mm beam diameter. The modulator transient time response for the previous silicon AOM is 480 ns with a 0.1 mm beam diameter, 400 ns with 0.3 mm beam diameter, and 275 ns with a 0.5 mm beam diameter.

Figure 7 shows the variations in the modulation contrast ratio in relation to the laser beam diameter for the previous and proposed AOMs at room temperature. The modulation contrast ratio for AlInGaAs AOM is 0.3 dB with a 0.1 mm beam diameter, 1.2 dB with a 0.3 mm beam diameter, and 4.8 dB with a 0.5 mm beam diameter. The modulation contrast ratio for SiGeO$_2$ AOM is 0.2 dB with a 0.1 mm beam diameter, 0.8 dB with a 0.3 mm beam diameter, and 3.2 dB with a 0.5 mm beam diameter. The modulation contrast ratio for the previous silicon AOM is 0.1 dB with a 0.1 mm beam diameter, 0.4 dB with a 0.3 mm beam diameter, and 1.6 dB with a 0.5 mm beam diameter.

Figure 8 illustrates the variation in the signal Q Factor in relation to ambient temperature for the previous and proposed AOMs. The Q Factor for AlInGaAs AOM is 15 at room temperature, 8.5 at 375 K, and 3.65 at 450 K. The Q Factor for SiGeO$_2$ AOM is 12 at room temperature, 8 at 375 K, and 3 at 450 K. The Q Factor for the previous silicon AOM is 10 at room temperature, 7 at 375 K, and 2 at 450 K.
We have studied the different AlInGaAs and SiGeO$_2$ AOMs under the same ambient temperature and diameter. All of the positive results focused on the proposed AOMs under the same ambient temperature and diameter of laser beam variations. Therefore, AlInGaAs is the best choice for upgrading wideband AO modulators in fiber optic communications.

4 Conclusion

We have studied the different AlInGaAs and SiGeO$_2$ acousto optic modulators for upgrading fiber optic communication systems. AlInGaAs AOM presented the highest Q factor, modulation contrast ratio, modulation speed response, and the lowest transient time speed response in comparison to the previous silicon AOM. Modulation frequency, frequency response, and rise time were also evaluated. All of the positive results focused on the proposed AOMs under the same ambient temperature and diameter of laser beam variations. Therefore, AlInGaAs is the best choice for upgrading wideband AO modulators in fiber optic communications.

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