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Review

Theoretical and experimental study of the light deflection by a frequency modulated ultrasonic wave

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ABSTRACT

A formula that describes angular excursion variation of an acousto-optical deflector is theoretically demonstrated and experimentally confirmed. This deflector is obtained using a laser beam interaction with a frequency modulated ultrasonic sinusoidal wave in a liquid medium. The obtained results show that each diffracted order position varies sinusoidally around its central position, in the same rhythm as the modulating signal. Moreover, the scanning frequency of the diffraction order increases linearly according to the modulating signal frequency. Furthermore, the increase in the frequency excursion leads to the increase of the angular excursion. All the theoretical results are confirmed experimentally. Finally, the frequency modulation index has been easily obtained with good precision using experimental measurements of the diffracted order angular excursion.

Contents

1. Introduction

Acousto-optic devices are based on photoelastic or elastooptic effect according to which an ultrasonic wave applied to an elastic medium, produces a strain which changes its refractive index. The light interaction with this medium provokes the diffraction phenomenon [1]. The obtained diffraction orders depend on the shape, the amplitude and the frequency of this ultrasonic wave. When this last is sinusoidal, the intensity and the position of the diffracted orders are constant, this diffraction has been explained by Raman and Nath and many other authors [1,2]. In case where sinusoidal ultrasonic wave is amplitude modulated (AM), the diffraction orders position remains constant, it was also observed that besides these diffracted orders, the spectrum showed satellite diffracted orders. This diffraction was performed for the first time by Pancholy and Parthasarathy and explained mathematically by Mertens and Hereman [3,4].

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In the case where ultrasonic wave is frequency modulated (FM) by a periodic signal, the position of the diffracted orders varies according to this modulating signal as presented by some authors who used these techniques for making deflectors and scanners for different scientific fields for making deflectors and scanners for different scientific fields [5–8]. To our knowledge, a rigorous theoretical development of light diffraction by a frequency modulated signal has not been done before. In this work we propose, analyze and experimentally demonstrate this phenomenon, starting from the diffraction relation [9,10], to finally reach a very important relationship between the diffraction orders positions and the modulating signal. Experiments on the scanning frequency and the angular excursion variation of the diffraction orders, as a function of the modulation frequency, were performed to confirm the obtained relationship.

In addition, we demonstrated that it is possible to obtain experimentally the frequency modulation index by measuring the angular excursion of the diffracted order. This operation was performed before using only a spectrum analyzer [11].

2. Theoretical development

Let $A(t)$ be an electrical frequency modulated signal, which its instantaneous frequency is modified according to a linear law by a modulating signal $S(t)$ [11]:

$$A(t) = A_a \cdot \cos\left[\omega_a t + C\int S(t)dt\right] \tag{1}$$

where A_a and ω_a stand for the amplitude and the pulsation of the carrier wave respectively and C represents the sensitivity of the modulator.

If $S(t)$ is cosinusoidal:

$$S(t) = A_m \cdot \cos(\omega_m t) \tag{2}$$

where A_m and $\omega_m = 2\pi f_m$ are the amplitude and the pulsation of the modulating signal.

Eq. (1) becomes:

$$A(t) = A_a \cdot \cos\left[\omega_a t + \frac{\Delta f}{f_m}\sin(\omega_m t)\right] \tag{3}$$

where $\Delta f = A_m \cdot C$, represents the frequency excursion. The instantaneous frequency $f(t)$ of the signal $A(t)$ can be written as follows:

$$f(t) = f_a + \Delta f\cos(\omega_m t) \tag{4}$$

This electrical signal $A(t)$ is converted to a longitudinal acoustic wave via piezoelectric effect [12]. The output acoustic power delivered by the transducer depends on the mismatch between the outer acoustic impedance of the transducer and the liquid acoustic impedance [13]. When this acoustic wave propagates in a liquid medium it gives rise to density variations $\Delta\rho/\rho_o$ (called condensation) brought about by hydrostatic pressure [14]. In water, the elasto-optical tensor is reduced to a constant value equals 0.31 [15]. The traveling acoustic wave sets up a spatio-temporel modulation of the refractive index [16]. In addition, the highest acoustic signal frequency that can propagate into a liquid medium cannot exceed 50 MHz due to acoustic losses [17].

The medium refractive index n_o, which was initially constant, becomes $n(x, t)$. It varies according to the electrical signal $A(t)$. The obtained variation of the refractive index can be written as follows:

$$n(x,t) = n_0 + \Delta n\left\{\sin\left[\omega_a t - k_a x + \frac{\Delta f}{f_m}\sin(\omega_m t - k_m x)\right]\right\} \tag{5}$$

where n_0 is the average refractive index of the medium, Δn stands for the index variation amplitude due to the acoustic wave, k_a *and* k_m are the wave numbers of the carrier and the modulating wave respectively and x is the propagation direction of the acoustic wave.

It is clear from Eq. (5) that the refractive index varies in time and space. We note that for $\Delta f = 0$ the refractive index will be given without frequency modulation, as it was given in previous references [1,19–21].

The acoustic wave propagation in the transparent medium provides a moving phase grating which may diffract portions of an incident laser beam into one or more directions. Under Raman-Nath regime, the output laser beam field $E_o(x, z, t)$ can be written as [3,21,22]:

$$E_o(x,z,t) = E_0 \exp j(\omega_0 t - k_0 z)\exp -jk_0 L \cdot n(x,t)$$

where E_0, k_0 and ω_0 are the amplitude, the wave number and the pulsation of the incident laser beam respectively, z represents the laser beam propagation direction and L is the interaction length.

At a certain distance from the AO cell, the diffracted light field can be described in the plane (X, Y) by the following relationship [9,10]:

$$\begin{aligned} E(X,t) = {} & E_0 \cdot \frac{\exp(jk_0 z)}{j\lambda_0 z} \cdot \exp j\left(k_0 \frac{X^2}{2z}\right) \\ & \cdot \exp j\left(\omega_0 t - k_0 z - \frac{2\pi n_0 L}{\lambda_0}\right) \cdot \sum_{p=-\infty}^{+\infty} \exp -jp(\omega_a t) \\ & \cdot J_p\left(\frac{2\pi L\Delta n}{\lambda_0}\right) \cdot \exp -jp\frac{\Delta f}{f_m}[\sin(\omega_m t)] \\ & \cdot \delta\left[\frac{X_p(t)}{\lambda_0 z} - \frac{p}{\lambda_a} - p\frac{\Delta f}{V}\cos(\omega_m t)\right] \end{aligned} \tag{6}$$

where $J_p(\Psi = 2\pi L\Delta n/\lambda_0)$ is the p^{th} order Bessel function of the first kind and of parameter Ψ [3], V is the ultrasonic wave velocity in the medium and δ represents the Dirac function.

Starting from Eq. (6) and using the Dirac function definition (Appendix A), we deduce a very interesting relationship of the diffraction orders:

$$\frac{X_p(t)}{z} = p\frac{\lambda_0 \cdot f_a}{V} + p\frac{\lambda_0 \cdot \Delta f}{V}\cos(\omega_m t)$$

$$\Rightarrow \theta_p(t) \approx \tan[\theta_p(t)] = \frac{X_p(t)}{z} = \theta_{pmed} + \Delta\theta_p\cos(\omega_m t) \tag{7}$$

With $\Delta\theta_p$ is the angular excursion and $\theta_p(t)$ represents the diffraction angles for $p = 0, \pm 1, \pm 2, \pm 3\ldots$.

- This equation contains two parts; a constant part $\theta_{p\ med}$ which represents the angle of p^{th} diffracted order without modulation as shown in Fig. 1a and the second one, which depends on time, describes theoretically the diffracted orders deflection around a central position $\theta_{p\ med}$ of the scanned area as presented in Fig. 1b.
- It is obvious, from Fig. 1b, that the diffracted orders positions vary in sinusoidal manner with time, where ($T_m = 1/f_m$) represents the period of the modulating signal as presented in Eq. (2). In addition, the angular excursion of each diffracted order $\Delta\theta_p$ depends on two parameters; the diffracted order number p and the frequency excursion Δf as indicated in the following relationship:

$$\Delta\theta_p = p \cdot \frac{\Delta f \cdot \lambda_0}{V} \tag{8}$$

3. Experimental setup and procedure

Details of the experimental setup are given in Fig. 2.