Ultrasound-tunable dispersive optical medium

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Abstract

There is considered designing materials with real-time variable dispersion characteristics and tunable spectral optical properties. It is based on dynamical structures technique generated in a medium by ultrasonic waves

1. Introduction

Metamaterial is a media exhibiting unusual electromagnetic properties, in particular non-trivial dispersion characteristics. One of the most universal approaches to variation and control of material dispersion is modulation of the medium, e.g. periodical structure generation by means of ultrasonic waves. These structures have similar features as volume phase diffraction gratings and provides spectral selection of optical radiation and selective control of laser beams [1]. Such a technique is named acousto-optical (AO) control and it is the basis of a family of tunable optical devices [2].

Now, all the widely-used AO devices operate definitely as diffraction elements, whereas their capabilities as dispersion elements have not used adequately and even has not recognized completely yet. However just in this implementation of optical element possessing tunable characteristics, AO cell can be regarded as reconfigural medium.

In the paper, various techniques of crystals dispersion control via acoustic field are analyzed, a group of AO devices are described, and future trends and prospects are discussed.

2. Dispersion control methods

The shape of transmission function T_{dif} for AO cell depends on the amplitude distribution of ultrasonic wave,

$$T_{dif}\left(\Delta k, t\right) : \left| \int_0^L S\left(t - x/V\right) e^{i\Delta k x} \cdot dx \right|^2 \tag{1}$$

where S – complex amplitude of propagating acoustic wave, V – sound velocity, L – medium length, $\Delta k = 2\pi\ (\Delta n/\lambda - f/V)$ – wave mismatch, displaying deviation of wavelength λ from the optimum value determined by ultrasound frequency f. Therefore, variation of the distribution as well as frequency of ultrasound can be used as method of medium dispersion control.

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There are two principle approaches to frequency control: (i) multi-frequency gratings and (ii) periodical modulation (fig.1). First of them require generation of several gratings of different frequency. If they are apart each other more than their bandwidths one can produce multi-pass or multi-stopband dispersion characteristic similar to photonic crystal bandstructure.

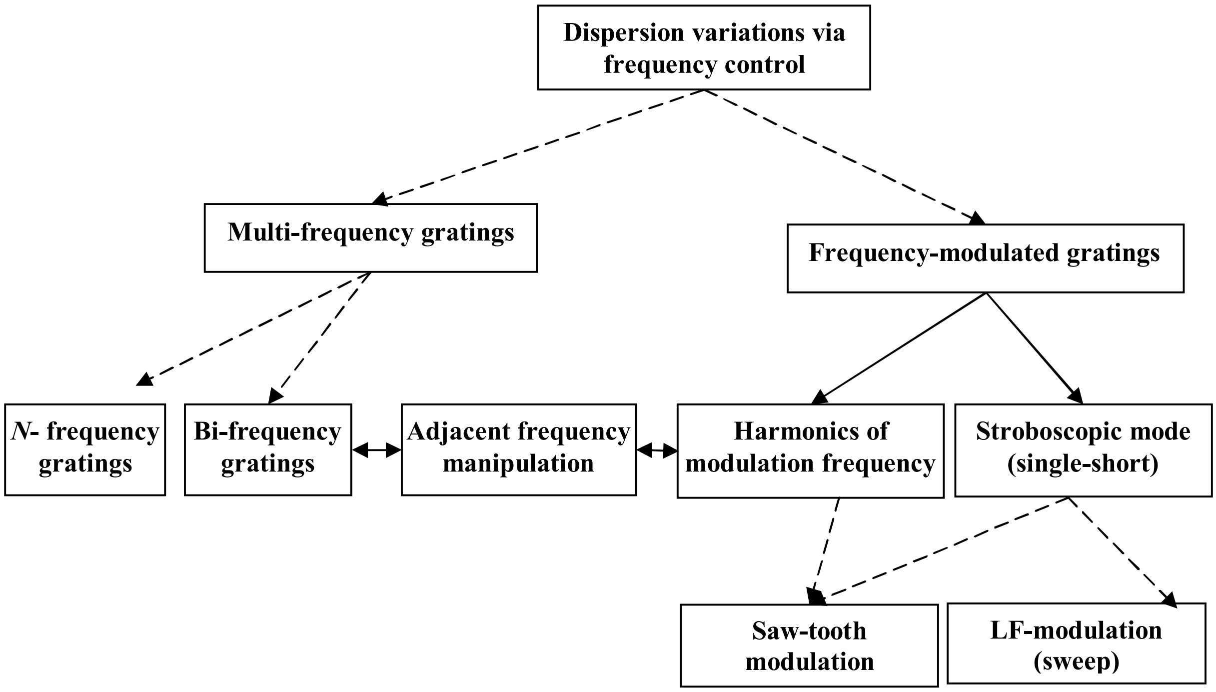

Fig. 1: Classification of modern techniques for dispersion control .

The second approach is based on ultrasonic-wave modulation resulting in diffraction-grating variation. This technique can be employed in two different ways. First one is targeted at creation of predetermined ultrasound distribution along the crystal (grating frequency profile). It can be efficiently applied for detection of single optical pulses or their periodical train. However, there are a permanent drift of grating leading to corresponding change of transfer function of the medium. The desired profile can be reproduced with a period not less then transit time of ultrasonic wave $\tau = L/V$.

Regarding grating instability we developed [3] new analytical method based on detection different frequency components of diffracted optical radiation modulated by non-stationary grating, particularly on modulation frequncy $f_{\mathrm{mod}} = 1/\tau$ and on the harmonics, and also time-averaged signal. This method presume detection of both the amplitude of the signal and the phase shift regarding to ultrasound modulation signal. As a result, the transfer function is complex-valued one.

3. Dispersion-controlled devices

Linear frequency (LF) modulation is the most useful distribution, which is applicable for various important applications. It is demonstrated experimentally and by calculations that LF modulation provides transmission “window” of variable width and rectangular-like shape, while transmission factor approaches 100%. Such a window can be swept over the spectrum for continuous monitoring.

As well LF modulation is used for generation of ‘chirped’ diffraction gratings, which are used for compression of ultra-short light pulses [4]. Nowadays, such AO instruments are used in installations for laser nuclear synthesis in order to compress optical pulses and to optimise their characteristics [5].

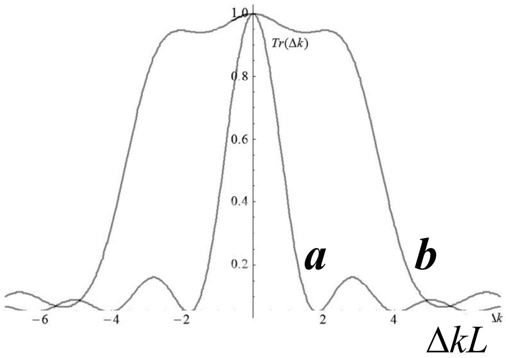

Fig. 2: Transfer function transformation via ultrasound frequency control:
a) classical diffraction-limited function; b) wide-band window provided by LF-modulation.

Phase modulation is also used for dispersion-control. Periodical reversal phase shift manipulation provides sign-reversing transfer functions of AO cell, which is a key element of the unique spectrometer for detection of differential characteristics [6].

4. Conclusion

Variation of ultrasound characteristics makes possible comprehensive control of dispersion characteristics of the medium. The most difficult task of this approach is to determine optimal interaction configuration (“geometry”), optimal mode and parameters of modulation.

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