Tomographic imaging by two-wave mixing with a wavelength-scanning laser diode

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A method of tomographic imaging is proposed in which two-wave mixing in a photorefractive crystal is used with wavelength scanning of a laser diode and phase modulation of the pump beam. This method provides full optical processing and is effective for weak light from objects because of the use of two-wave mixing. The depth resolution of the method was ~1 cm when the wavelength-scanning width was ~0.02 nm. © 2000 Optical Society of America

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In tomographic imaging based on optical interferometry there are two basic methods, optical coherence-domain reflectometry and optical frequency-domain reflectometry. Optical coherence-domain reflectometry utilizes the characteristics of the coherence function of a light source. A low-coherence source such as a superluminescent diode is used to obtain a strong interference signal only when the optical path difference (OPD) is nearly zero.[1,2] Tomographic imaging along the depth direction in a three-dimensional object is achieved by scanning of a reference mirror. The scanning of the reference mirror is eliminated by synthesis of a desirable coherence function for generation of strong interference at a specified OPD. When synthesis of the coherence function is obtained by modulation of the optical wavelength of a laser diode (LD) and its optical phase in the time domain,[3] integration of the time-varying interference pattern leads to a tomographic image. When synthesis of the coherence function is achieved by manipulation of the phases of spatially dispersed wavelength components of a superluminescent diode in the space domain,[4] a strong interference pattern is generated at a specified OPD, resulting in a tomographic image. On the other hand, optical frequency-domain reflectometry utilizes the characteristics of a time-varying interference signal detected when the wavelength of a light source is continuously scanned in the time domain[5,6] or the space domain.[7] The interference signal is processed with a computer[5,7] or by electronic tuning[6] to yield tomographic images. Among the techniques of tomographic imaging described above, to our knowledge full optical processing without numerical and mechanical processing was realized only in Ref. 3. A key point in achieving full optical processing is to generate a tomographic image from a stationary interference pattern that is caused by the two waves with a specified OPD.

In this Letter we produce a stationary interference pattern in a photorefractive crystal by two-wave mixing for generation of an image. An interference pattern corresponding to a specified OPD is made stationary by linear phase modulation of the reference beam and wavelength scanning of the LD. Since the magnitude of the linear phase modulation of the interference pattern that is due to the wavelength scanning is proportional to an OPD, a tomographic image is generated by a change of the width of the wavelength scanning. Moreover, a weak signal beam from the objects is amplified by two-wave mixing. This characteristic is unique to the technique of tomographic imaging described here.

Figure 1 shows a setup in which two-wave mixing is performed with a $BaTiO_3$ crystal. The output beam from a LD is collimated by lens 1 (L1), and the collimated beam is divided by a beam splitter (BS). A pump beam from mirror M is vibrated by a piezoelectric transducer (PZT) with a sawtooth wave of frequency f_p; this produces linear phase modulation, as shown in Fig. 2. A signal wave comes from objects O_1 and O_2, and its intensity is adjusted with a density filter (DF). Images of the object surfaces are made in the crystal with lens 2 (L2). The injection current of the LD changes with time as follows:

$$I_c(t) = I_0 + bt, \quad 0 \le t \le p/f_p, \tag{1}$$

where p is a positive integer. The injection current reaches the maximum value I_H at $t = p/f_p$. Figure 2

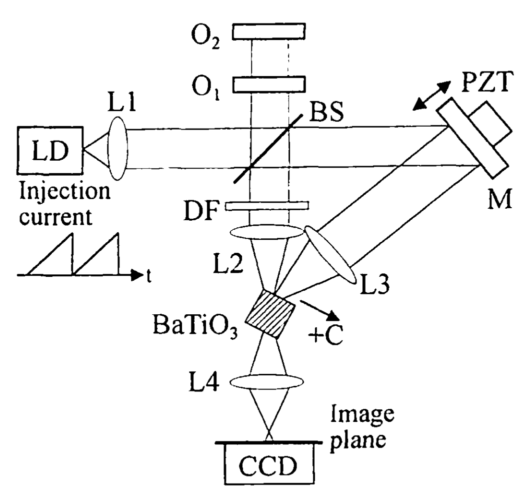

Fig. 1. Setup for tomographic imaging by two-wave mixing with wavelength scanning of the LD and phase modulation of the pump beam. Abbreviations defined in text.

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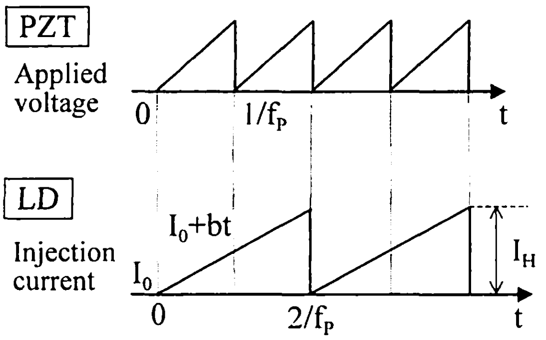

Fig. 2. Voltage applied to the PZT and injection current of the LD, which generates linear phase-modulation and wavelength scanning, respectively, where $p = 2$.

shows the case of $p = 2$. When the injection current increases from I_0 by bt, the wavelength λ of the LD increases from λ_0 by βbt. Since a small amplitude of the vibration of the PZT is desirable for linear and continuous phase modulation of the pump beam, the amplitude is adjusted to be $\lambda/2$. In this phase modulation, wavelength λ can be regarded as a constant value λ_0 because $\beta I_H \simeq \lambda_0 \times 10^{-4}$. Considering an object whose surface position is expressed as L, we note that a time-varying OPD between the signal and the pump beams at some points in the crystal is given by

$$L_t = L + f_p \lambda_0 t\,. \tag{2}$$

Wavelength scanning of the LD produces the time-varying phase of the interference fringe, which is regarded as a linear function of t:

$$\phi_f(t) = 2\pi L_t/\lambda = 2\pi L_t/\lambda_0 - 2\pi(\beta b/\lambda_0{}^2)L_t t\,, \quad 0 \le t \le p/f_p\,. \tag{3}$$

Substituting Eq. (2) into Eq. (3) and neglecting the terms containing t^2, we have

$$\phi_f(t) = 2\pi L/\lambda_0 + 2\pi f_p t - 2\pi(\beta b/\lambda_0{}^2)Lt\,, \quad 0 \le t \le p/f_p\,. \tag{4}$$

An index grating is generated in the crystal by exposure of the interference fringe between the signal and the pump beams. The running of the interference fringe must be smooth for the signal beam to be amplified by the two-wave mixing. Maximum amplification occurs when the interference fringe is stationary with time. However, we do not consider where the stationary fringe is produced in the crystal. A conclusion of the analysis obtained from Eq. (4) is that a signal beam with OPD

$$L = \lambda_0{}^2 f_p/\beta b = p\lambda_0{}^2 \beta I_H \tag{5}$$

is amplified by two-wave mixing. The beam that is diffracted by the index grating from the pump beam is imaged with lens 4 (L4; Fig. 1) and its image is detected on the image plane with a CCD image sensor (CCD). By changing the value of I_H, we selectively obtain the image of an object, whose position is given by Eq. (5), among many objects located at different positions.

In the experimental setup the wavelength λ_0 and the output power of the LD were 658 nm and 30 mW, respectively. The frequency of f_p was 24 Hz, and the voltage signal applied to the PZT was synchronized with the signal of the injection current in the condition $p = 2$. The focal length of L2 and L3 was 70 mm. The angle and the intensity ratio R between the pump and the signal beams were ~30° and 500, respectively. A vinyl sheet with thickness and transmittance of ~0.1 mm and 97%, respectively, was used as an object. We detected an interference signal between the diffracted pump beam and the signal beam on the image plane with a photodiode when there were no phase modulations and R was less than 10. After that the amplitude of the vibration of the PZT was adjusted by observation of the interference signal before the index grating disappeared owing to phase modulation of the PZT.

First, we placed the same vinyl sheet at positions $L =$ 4 cm and $L = 6$ cm, as shown in Fig. 1. We changed the value of I_H at intervals of 0.2 mA and detected the intensity of the light diffracted from the pump beam on a point of the image plane. The result is shown in Fig. 3. A peak of the intensity of the diffracted light I_D appears at $I_H = {\sim}3$ mA, corresponding to the object position at $L = 6$ cm. Another peak is at $I_H = {\sim}4$ mA, corresponding to $L = 4$ cm. Since the product of $L \times I_H$ is not constant in this experiment, it is assumed, from Eq. (5), that the coefficient β was not always constant. Although some theoretical analysis is required for the intensity distribution of the diffracted light I_D to be obtained, the result shown in Fig. 3 indicates clearly that we can distinguish two objects that are 1 cm apart.

Next we used two vinyl sheets of the same size, on which dark lines were drawn on each half of the sheets, as objects O_1 and O_2. Images 1 and 2 of the objects are shown in Fig. 4(a), in which the width and the space of the lines were 0.25 and 0.50 mm, respectively. The positions of objects O_1 and O_2 were 4 and 6 cm, respectively. The beam profile that was incident upon the objects was Gaussian with an elliptical shape. Images detected with the CCD image sensor on the image plane for different values of I_H

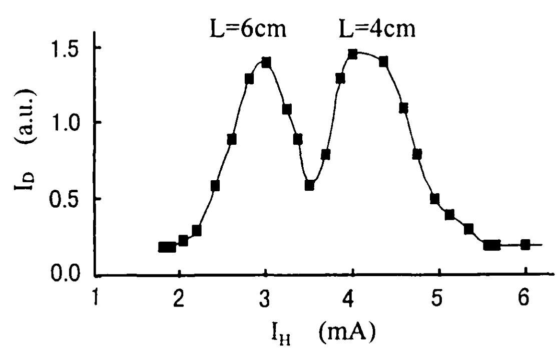

Fig. 3. Injection current I_H versus intensity I_D of the light diffracted from the pump beam for the two objects at $L =$ 4 cm and $L = 6$ cm.

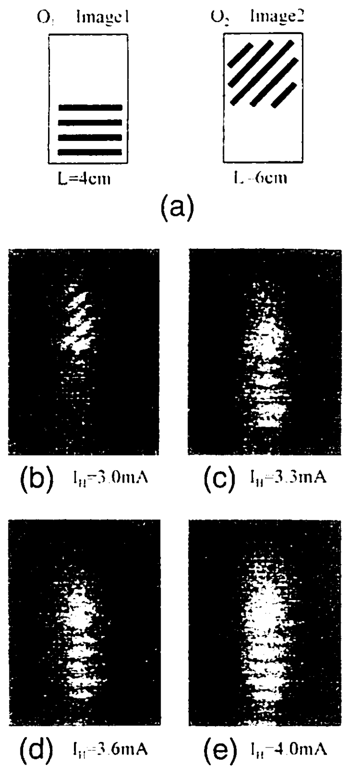

Fig. 4. (a) Images 1 and 2 of the two objects at $L = 4$ cm and $L = 6$ cm. (b)–(e) Images detected with the CCD image sensor at (b) $I_H = 3.0$ mA, (c) $I_H = 3.3$ mA, (d) $I_H = 3.6$ mA, and (e) $I_H = 4.0$ mA. Images 2 and 1 appear in the detected images in (b) and (e), respectively.

are shown in Figs. 4(b)–4(e). Images 2 and 1 appear in the detected images of Figs. 4(b) and 4(e), in which I_H is 3.0 mA and 4.0 mA, respectively. In Fig. 4(b) a weak shadow of image 1 appears on the bottom part of image 2. A strong shadow of image 1 appears in the detected image in Fig. 4(c) at $I_H = 3.3$ mA. The detected images are consistent with what we expect from the result shown in Fig. 3.

We have proposed a method of tomographic imaging in which two-wave mixing in a photorefractive crystal was used with wavelength scanning of the laser diode and phase modulation of the pump beam. The method is unique in that full optical processing is effective for weak light from the objects. The depth resolution, which was nearly in inverse proportion to the wavelength-scanning width βI_H, was ~1 cm when the coefficient β was ~0.005 nm/mA. We are now using a tunable laser diode with an external cavity, and the depth resolution is being improved to ~0.1 mm. It may be possible to apply this method to some biotissue. In future applications we plan to give more-detailed consideration to forming the index grating and imaging of scattering media.

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