Vol 11 No 7, July 2002
1009-1963/2002/11(07)/0710-04

Chinese Physics

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Optically fixed photorefractive correlator*

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(Received 26 November 2001; revised manuscript received 24 February 2002)

An optically fixed photorefractive correlator is presented, where two-centre non-volatile holographic recording is employed to write and fix the matched filter in doubly doped $LiNbO_3$ crystals. This correlator shows good correlation characteristics and insensitivity to the writing beam during readout. It can be used in cases requiring stability and not requiring modification for a long period, and it is refreshed optically when new information needs to be registered.

Keywords: photorefractive effect, two-centre non-volatile holographic recording, correlator, doubly doped $LiNbO_3$ crystals

PACC: 4240, 4265, 4280

1. Introduction

Photorefractive crystals play an important role in holographic storage and real-time optical correlators.[1] In general, photorefractive crystals are used as materials of volume holograms. Diffraction from volume holograms obeys the Bragg condition. As a result, the hologram exhibits strong angular or spectral selectivity.[2] These features can be used in angle-multiplex holographic storage and holographic filters. Although the performance of the photorefractive matched filter, such as its shift and rotation tolerance, is constrained by the Bragg condition, it provides the possibility for multiple pattern matched filter construction.

The gradual erasure of holograms stored in photorefractive matched filters during readout is due to the effect of charge redistribution produced by the reading beam whose wavelength is the same as that of the writing beam. Thermal fixing is a solution to the destructive readout,[3] but it is difficult to process in real-time and *in situ*, and it is impossible to erase promptly and optically because the ionic grating, which is a replica of the electronic grating, is insensitive to the reading beam. Recently, Buse *et al*[4] proposed a resolution to the volatility that $LiNbO_3$:Fe:Mn crystals can be used for holographic recording with both an ultraviolet (UV) light for sensitizing and a red light interfering intensity for recording, which is referred to as two-centre holographic recording. The suggested method consists of three processing phases of pre-exposure, hologram recording and optical fixing. In the pre-exposure phase, a UV light is utilized to transfer the electrons from the deep traps (manganese) to the shallow traps (iron) through the conduction band, which increases the absorption of crystal (i.e. via the photochromic effect) for holographic recording with the red light. In the second phase, the crystal is illuminated simultaneously with a UV light and a red interfering pattern, so that the information carried by the red pattern will be recorded in the shallow and deep traps. Switching the UV light off and illuminating the crystal with a homogeneous red light, the electrons will be moved eventually from the shallow traps back to the deep traps. This results in a photorefractive hologram optically fixed in the deep traps (manganese) that persists against further red illumination. However, the desired optical erasure of the fixed hologram is still possible by exposure to the UV or other light of short wavelengths again. When the matched filter needs be refreshed and new information registered, the stored holograms in the photorefractive matched filter can be erased optically and promptly.

Recently, we reported on the two-centre holographic recording in $LiNbO_3$:Cu:Ce crystals (Cu and Ce act as the deep and shallow centres, respectively).[5] The crystals have the capacities of non-volatile holographic recording with high persis-

*Project supported by the National Natural Science Foundation of China (Grant No 69837020) and the Natural Science Foundation of the Education Department of Jiangsu Province, China (Grant No 01KJB140008).

tent diffraction efficiency and weak light-induced scattering in contrast to $LiNbO_3$:Fe:Mn crystals.[6,7] In this paper, we present an optically photorefractive correlator where the matched filter is written and fixed in $LiNbO_3$:Cu:Ce crystal using the two-centre holographic recording method. This correlator shows good correlation characteristics and insensitivity to writing beam during readout. It can be used in cases requiring stability but not requiring modification for a long period, and can be refreshed optically when new information needs to be registered.

2. Basic principles and experimental method

Figure 1 shows the functional block diagram of the VanderLugt optical correlator based on the correlation theorem,[8,9] $U \otimes R = F^{-1}\{F\{U\} \cdot F\{R\}\}$, where R and U represent two two-dimensional objects, and $R \otimes U$ represents the correlation function of R and U. The multiplication operation on the right-hand side can be implemented by holographic writing and reading. In this case, the hologram is written by the interference of the Fourier transform $F\{R\}$ of the reference object and a plane reference beam. The readout is done using the Fourier transform $F\{U\}$ of the unknown object as an input beam. The result of the multiplication $F\{R\} \cdot F\{U\}$ is proportional to the intensity of the diffracted beam. The inverse Fourier transform of $F\{R\} \cdot F\{U\}$ can be performed again by another lens.

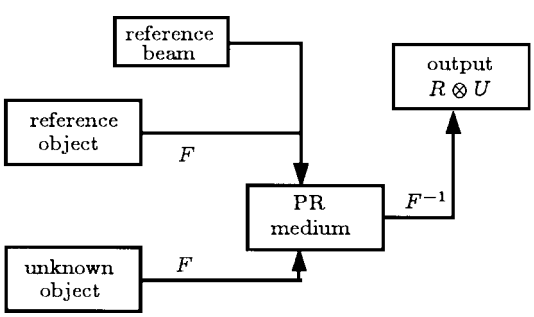


Fig.1. Flow diagram for the correlation operation. F and F^{-1} represent Fourier and inverse Fourier transform operations, respectively.

Figure 2 shows a schematic diagram of the experimental set-up of the optically fixed photorefractive correlator. In our experiments, because we aim to obtain an optically fixed photorefractive correlator, which can be processed optically in real time and *in situ*, a doubly doped $LiNbO_3$:Cu:Ce crystal is used as the holographic material. The lithium niobate crystals are doped with 0.011wt% CuO and 0.085wt% Ce_2O_3 in melt and grown in air by the Czochralski method, and are oxidized by annealing at 900°C in air for 6h. This material has good capacities of two-centre recording with high persistent diffraction efficiency and weak light-induced scattering.[5] The sample is $10 \times 10 \times 2\,mm^3$ in size and is oriented with the c-axis parallel to its large faces. As shown in Fig.2, in the process of recording the holographic matched filter, a red beam of 633 nm from a He–Ne laser is used for writing, while an expanded blue beam of 458 nm from Ar^+ laser is used for sensitizing, which covers the recorded region. The red beam is split into an object beam, which is expanded and collimated to illuminate the object input plane, and a plane-wave reference beam. The lens $L1$ generates the complex Fourier transform field of the input reference object R that interferes with the plane-wave reference beam in the sample of $LiNbO_3$ crystal. After writing, the sensitizing beam and the object beam are off, and the reference beam is incident on the crystal to fix the written hologram until all electrons are trapped in the Cu deep centres, i.e. to the fixing steady state. In the readout process, the unknown object is in the input plane H and its Fourier transform is incident on the crystal. The diffraction beam intensity is proportional to the product of the Fourier transforms of the reference and unknown objects. A CCD sensor located in the Fourier plane of the other Fourier lens $L2$ captures the correlation peak which is then displayed on a monitor. Figures 3(a) and (b) show a typical displayed correlation peak and its intensity profile between unknown and reference objects, respectively. As shown in Fig.3, the correlator has a good signal-to-noise ratio.

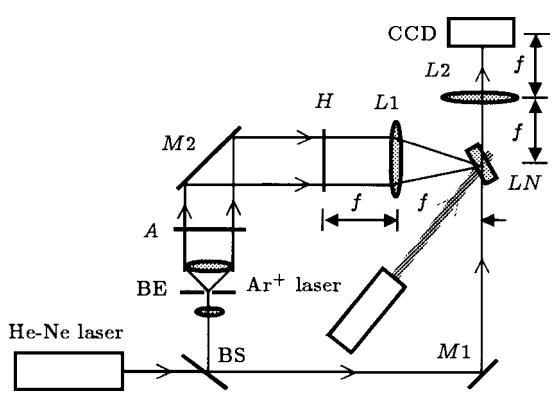


Fig.2. Experimental set-up for optically fixed photorefractive correlator: BS, beamsplitter; BE, beam expander with spatial filter consisting of a 20× microscope objective and a 10μm pinhole; A, attenuator; $M1$ and $M2$, mirrors; LN, $LiNbO_3$ doped with Cu and Ce crystals; H, input plane; $L1$ and $L2$, Fourier transform lenses (focal length 30cm).

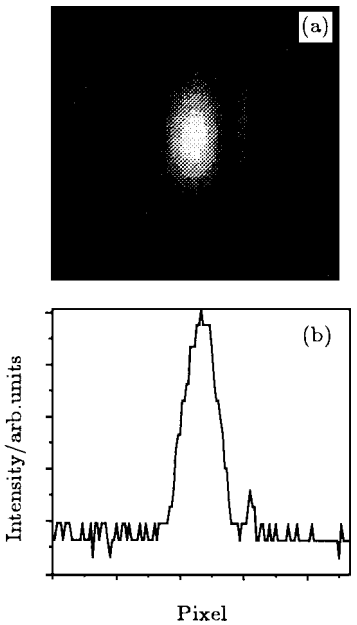


Fig.3. (a) Output of the correlation peak between unknown and reference objects. (b) The profile of the correlation peak.

3. Performance of the optically fixed photorefractive correlator

In all our experiments, the reference object is the letter 'F', and the matched filter is recorded and fixed in the sample using the two two-centre holographic recording methods mentioned above. Figure 4 shows the profiles of the output correlation peak between the reference letter 'F' and unknown characters, F, E, H, L, N, T, V, W and Y. The difference in correlation response when the unknown character coincides or not with the reference is quite apparent. Because the character 'E' is similar to the character 'F', the correlation peak between them is also strong, while the correlation peaks between the character 'F' and other characters are weak due to non-similarity.

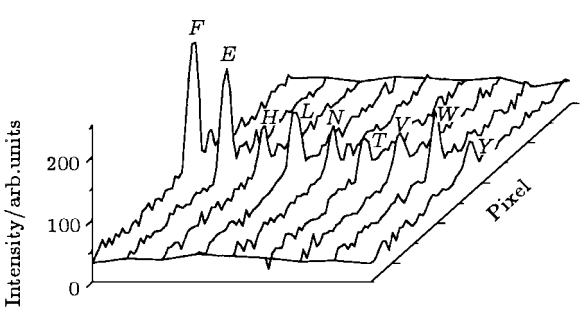


Fig.4. Profiles of output correlation peak between the reference letter F and unknown characters, F, E, H, L, N, T, V, W and Y.

This optical VanderLugt correlator based on the correlation theorem is not rotation- and size-invariant because it performs template matching only. We perform the non-rotation-invariance by rotating the unknown character 'F'. The unknown object is rotated 15 degrees per step, and the non-rotation-invariance behaviour is shown in Fig.5. In this way, it behaves as the conventional VanderLugt correlator. We also perform the non-size-invariance behaviour by varying the size of the unknown character 'F', and the experimental results are shown in Fig.6. The conventional VanderLugt correlator should be shift-invariant. However, a thick holographic material used as the matched filter, such as a photorefractive crystal, imposes strict Bragg angular selectivity that reduces the shift-invariance capability. This is due to the fact that, when the object is transversely shifted, its Fourier transform formed by the lens remains in the same position but the angles of beams forming each point have changed. We perform the shift-invariance correlation by shifting the unknown character 'F' transversely. The dimension of the unknown character 'F' is 3 cm and the shift step is 0.5 mm. The shift-tolerance of the experimental correlator is shown in Fig.7. The displacement is about 2.5 mm from the maximum correlation position when the intensity of correlation peak reduces to half the maximum intensity.

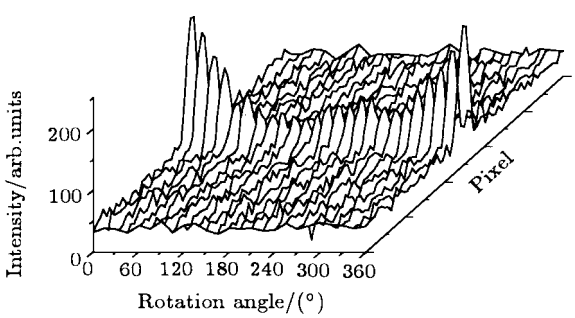


Fig.5. Non-rotation-invariance behaviour of the optically fixed photorefractive correlator; profiles of output correlation peak when the unknown character 'F' rotates.

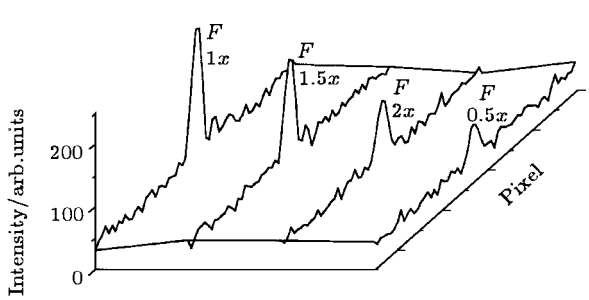


Fig.6. Non-size-invariance behaviour of the optically fixed photorefractive correlator; profiles of output correlation peak when the unknown character 'F' varies in size.

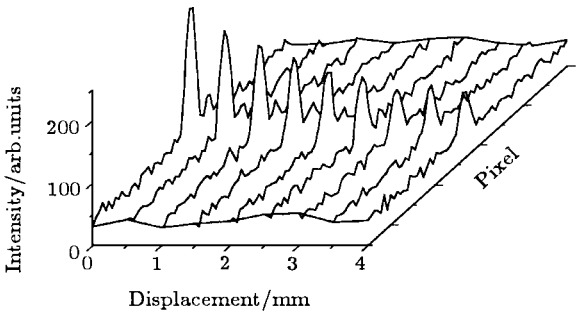


Fig.7. Shift tolerance of the optically fixed photorefractive correlator; profiles of output correlation peak when the unknown character 'F' shifts transversely.

After long-time readout, the intensity of correlation peak has no remarkable variation because the matched filter is fixed. When the matched filter is illuminated by the sensitizing beam of 458 nm, the autocorrelation peak becomes weak promptly down to disappearance because of the optical erasure of stored hologram in the matched filter, and new information can be registered again. Moreover, many Fourier transform holograms can be recorded with the angle multiplexing method[10] in the matched filter, so it provides the possibility for multiple pattern matched filter construction.

4. Conclusions

In this paper, an optically fixed photorefractive correlator is presented, where the two-centre nonvolatile holographic recording method is employed to write and fix optically the matched filter in doubly doped $LiNbO_3$:Cu:Ce crystals. Its correlation performances are studied experimentally. This correlator shows good correlation characteristics and insensitivity to the writing beam during readout. It can be used in cases requiring stability and not requiring modification for a long period, and it is refreshed optically when new information needs to be registered.

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