Interferometric test for the alignment of pump waves in photorefractive, externally pumped FWM

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ABSTRACT. Based upon two object-beams phase conjugation, a simple interferometric test to measure pump-waves misalingment in photorefractive, externally pumped FWM, is proposed. The procedure results in a null-test for perfect alignment.

RESUMEN. Basándose en la conjugación de fase con dos ondas objeto,se propone una prueba interferométrica capaz de medir el grado de alineación entre las ondas de bombeo de una mezcla fotorrefractiva de cuatro ondas externamente bombeada. El procedimiento deriva en una técnica de medición nula para alineación perfecta.

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A good quality of phase conjugate waves (PC waves) is required to use them as the basis of such applications as interferometry or imaging. Within the frame of externally pumped four-wave mixing (FWM), some theoretical aspects about those parameters which determine good conjugation have been discussed [1]. Regarding pump waves, these parameters include wave front quality of pump waves, pump waves' phases and pump waves alignment. Tests to check wave front quality of PC waves have been already proposed [2,3]. The role of the phases has been also both theoretically and experimentally discussed in Ref. [4]. The purpose of this letter relates to the third point, showing the possibility of a simple testing for proper alignment of external pump waves in FWM. Photorefractive FWM is emphasized.

To this end, consider two pump waves complex amplitudes of the form

$$A_j = a_j \exp[-i2\pi\alpha_j x] \quad (j = 1, 2), \tag{1}$$

where the a_j's can be complex functions of the transverse coordinates (x, y) subject to the condition $a_1 = a_2^*$. The value $\alpha_j = \sin[\theta_j]/\lambda$ measures the tilt of each pump wave with respect to the z-axis, λ being the corresponding wavelength and θ_j the tilt angle.

According to Cronin-Golomb *et al.* [5], when using a photorefractive crystal with negligible absorption as a PC mirror, the reflected PC wave A_3 can be shown to obey the following proportionality:

$$A_3 \propto \left[\frac{A_1 A_2}{A_1^* A_2^*}\right]^{1/2} A_4^*, \tag{2}$$

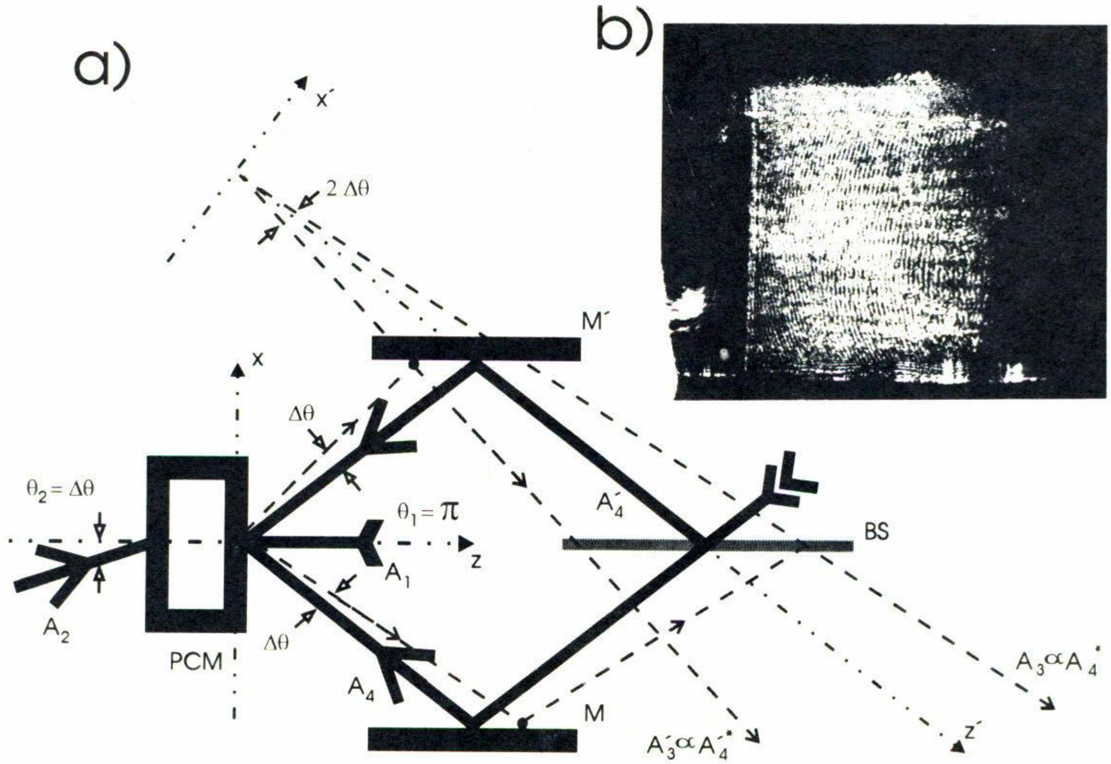

FIGURE 1. Two-signal FWM with external pump waves brought into misalignment. PCM, phase conjugate mirror. (x, y) coordinate system for FWM. (x', y'), coordinate system for PC waves. b) Typical interference pattern of the signal waves due to pump-waves misalignment (almost vertical dark fringes on a BGO sample's surface). With $\lambda = 514$ nm and a fringe period Λ of 0.073 cm (crystal's upper edge), from $\sin[\Delta\theta] = \lambda/2\Lambda$, $\Delta\theta \simeq 0.02°$ can be determined.

with A_4 the signal's complex amplitude to be conjugated. A possible path of A_4 is traced with solid lines along BS-M-PCM in Fig. 1, where BS denotes the beam splitter for PC detection and M indicates an adjusting mirror (or an optical system). By introducing another signal wave A_4' along BS-M'-PCM at some path other than that of A_4 (see Fig. 1a), two PC waves (A_3 and A_3') are to be expected emerging from the beam splitter BS toward detection. Their paths were drawn with dashed lines from PCM back to BS. In agreement with relation (2), A_3 must be proportional to $A_4^* \exp[i2\pi(\sin\theta_2 + \sin\theta_1)x/\lambda]$. A similar proportionally between A_3' and $A_4'^*$ holds. Interchange of energy between signals will not be considered. Without loss of generality, two symmetrical paths with respect to the beam splitter BS are drawn.

If the pump waves were plane waves in perfect counter-propagation, matching conditions for perfect conjugation, $A_1 = A_2^*$ would be fulfilled as well. In particular, that situation occurs when $\theta_1 = -\theta_2$, thereby leading to $\sin\theta_1 + \sin\theta_2 = 0$, and A_3, A_3' result just proportional to A_4^* and $A_4'^*$, respectively. Under these particular conditions, behind BS, A_3 and A_3' would travel essentially parallel to each other along the z'–axis, resembling a six-wave mixing scheme as reported in Ref. [6].

However, if a tilt between pump waves does exist, then θ_1 differs from $-\theta_2$, which implies that $\sin\theta_1 + \sin\theta_2 = \lambda\,\Delta\alpha \neq 0$ and, for small deviations where θ_1 is close to $-\theta_2$, condition $|\lambda\,\Delta\alpha| < 1$ can be accomplished. Thus, in that case, there exists an angle $\Delta\theta$ such that the spatial frequency $\Delta\alpha = \sin[\Delta\theta]/\lambda$. As a result, the PC waves propagate along directions differing from those of their respective signal waves by the same amount of $\Delta\theta$ (in Fig. 1a, $\theta_1 = \pi$ and, as a consequence, $\theta_2 = \Delta\theta$). After reflections in M and M$'$ respectively along the traveling path from the PCM to BS, tilt $\Delta\alpha$ causes an angle $2\Delta\theta$ between both PC waves to appear, as shown in Fig. 1a. Along the z'–direction behind BS, superposition of A_3 and A_3' leads to an interference irradiance pattern I given, in arbitrary units, by

$$I = |A_4|^2 + |A_4'|^2 + 2|A_4| \cdot |A_4'| \cos[4\pi\Delta\alpha\, x' + \Psi(x', y')] \quad (3)$$

where a coordinate system (x', y') as shown in Fig. 1a has been used, whereas $\Psi(x', y')$ accounts for additional phase shifts introduced mainly for the beam splitter and from terms of orders other than x' of the phase of the complex product $A_3 A_3'^*$. Such terms appear due to the PC generation process itself (photorefractive material, experimental conditions, and angular dependence, for example). Irrelevant constant factors have not been taken into account in Eq. (3) and the same PC reflectivity for both signals has been assumed.

A lateral shearing interferometer with a shear along x' is thus formed [7]. In particular, if $\Psi(x', y')$ is nearly constant, $\Delta\alpha$ can be measured from the resulting parallel interference fringes and the misalignment $\Delta\theta$ can be known. There is a factor 2 in Eq. (3) multiplying the spatial frequency $\Delta\alpha$ of the interference fringes. This factor brings a convenient extra sensitivity for misalignment measuring. An example of such an interference pattern can be seen at Fig. 1b for a BGO sample ($10 \times 10 \times 2$ mm^3, drift mode) in FMW configuration with two signal waves as described, and with the pump waves brought into misalignment. In this figure, fringes corresponding to pattern of Eq. (3) are nearly vertical fringes of low contrast. A second fringe pattern of higher contrast is superimposed (nearly horizontal fringes of higher spatial frequency). This second system arises from internal reflections within the crystal. Observation of the first pattern results in a valuable help to drive pump waves into proper alignment by looking for a dark field (due to the π–shift in the beam splitter if it is a conventional one) while adjusting the pump waves. Furthermore, stability of the pattern can give indication, in turn, of mechanical stability of the set-up's components involved in pump waves. Note that the beam splitter BS is always employed to watch the PC wave. So, the extra requirement to implement this test would probably be only the adjusting mirror M$'$ (or optical system).

Although a symmetrical two-signal configuration is sketched in Fig. 1a, it is not a necessary condition to be so (in practice, it can be convenient such configuration because it brings the possibility to become equal PC reflectivity for the signals). The point is that both signals must be generated from the same source and the observation must be done behind the beam splitter employed to form them (BS in Fig. 1a). Moreover, due to PC wave properties, alignment of the components forming the paths BS-M-PCM and PB-M'-PCM does not need to be very carefully adjusted.

In FWM based on the cubic nonlinear susceptibility a proportion like Eq. (2) is to be observed [8]. Therefore, the main conclusions shown for photorefractive FWM can by applicable. Although in a less direct analogy, this effect is expected to have a simile in non dynamic holography (A_4 and A'_4 added by recording a double-exposure hologram with the same reference A_1), where again proportions analogous to Eq. (2) hold (see for example Ref. [9]).

In conclusion, the possibility of a test for pump waves alignment in externally pumped FWM was experimentally probed in photorefractive BGO crystals.

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