Forced Reciprocity Using Phase Conjugation

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The various physical effects that are detected with interferometers can be classified into two types : the reciprocal effects and the non-reciprocal effects. The corresponding interferometers are the Michelson interferometer and the Sagnac interferometer. A particular interferometer is chosen according to the phenomenon to be detected. On the other hand, this interferometer is sensitive to all the phenomena of the corresponding class, and all the non-wanted effects add noise to the interesting signal. The signal is usually extracted by electronic filtering, which is difficult and expensive. We propose a new scheme of interferometer, sensitive either to reciprocal or non-reciprocal effects, depending on the conditions. In particular, low frequency reciprocal effects are not detected, so that there is no problem of long-time drift, often due to slowly varying reciprocal perturbations, whereas medium frequency reciprocal signals are detected. This interferometer has the stability properties of a non-reciprocal interferometer (i.e. Sagnac), but detects reciprocal events. Those properties are realized by replacing the mirrors of a Michelson interferometer by "conjugate mirrors", made out of a photorefractive material.

I - CONJUGATE MIRRORS

Photorefractive materials are both photoconductive and electrooptic, so that they can be used as sensitive materials for holographic recording. To build a phase volume hologram within such a crystal, a light interference pattern is created by directing two coherent laser beams (the reference and the signal beams) onto the crystal (fig. 1). Photocarriers are then generated proportional to the local intensity of the light, i.e. the intensity interference pattern. Those carriers move inside the crystal through different mechanisms (diffusion or drift under an electric field) and are trapped, so that the charge varies proportional to the illumi-

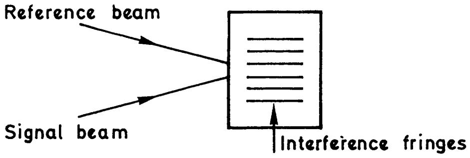

Fig. 1 Hologram in a photorefractive crystal

nation. This means that a space charge field is created, and varies as the local illumination, but with a phase displacement [3] (fig. 2). Finally, through electrooptic modulation, a phase hologram is created which bears the information of the signal beam. The materials used must be photoconductive, but this is true for most materials, because of impurities often trapped in the lattice. The other important feature is the electrooptic coefficient of the material. This is why the crystals commonly used are $B_{i12}SiO_{20}$ [1] or $BaTiO_3$. The coefficient of the baryum titanate, for example, is equal to $820 \cdot 10^{-12}$ e.s.U. which is one of the highest known electrooptic coefficients and it is the reason for recent work done on this material in connection with phase conjugation [2,4].

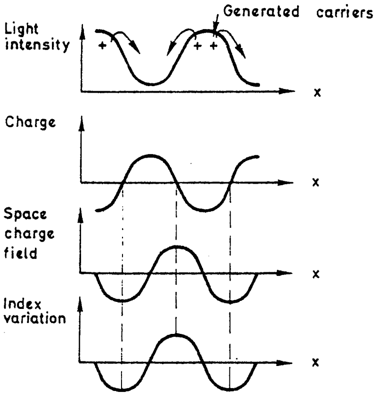

Fig. 2 Index modulation mechanism

A "conjugate mirror" is composed of a classical mirror and such a crystal, where the reference is reflected back to read out the hologram and generate the conjugate beam of the signal beam (fig. 3). This conjugate beam's amplitude is proportional to the complex conjugate of the amplitude of the signal beam. In particular, if the signal beam's phase is ϕ with respect to the reference beam, then the conjugate beam's phase is $-\phi$. This is due to the term

$$E^*_{signal} \cdot E_{reference}$$

of the amplitude of the hologram recorded ; the amplitude of the image beam after readout is that of the hologram multiplied by the amplitude of the readout beam

$$E_{conj.} = E^*_{signal} \cdot E_{reference} \cdot E_{readout}$$

This gives the expression of the phase of the conjugate beam.

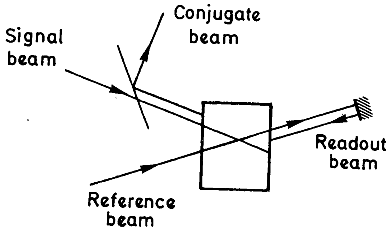

Fig. 3 A conjugate mirror

In the case where the readout beam is the reflected reference beam, and has the same phase, this gives

$$E_{conj.} = E^*_{signal} \cdot |E_{reference}|^2 \quad .$$

We will now show that both terms are equally important for the conjugate mirror interferometer.

II - MICHELSON INTERFEROMETER WITH CONJUGATE MIRROR

A Sagnac interferometer is sensitive to non-reciprocal phase perturbations, whereas a Michelson is mainly sensitive to reciprocal phase perturbations on one of the arms (fig. 4). If we replace the mirrors of a Michelson interferometer by conjugate mirrors, it becomes insensitive to reciprocal phase perturbations (fig. 5). But if there is a non-reciprocal phase shift on one of the arms, it is now detected (fig. 6) [7]. We will show that only one conjugate mirror is needed, so that the device becomes much simpler (fig. 7). In this device, the pump beam is actually one of arms of the interferometer. If there is a reciprocal phase shift on one of the arms, there is no change of the interference fringes at the output, whereas a non-reciprocal phase shift on either arm causes a fringe displacement.

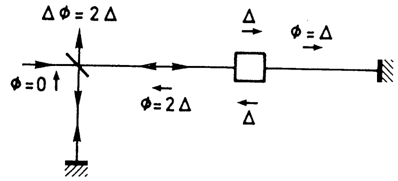

Fig. 4 Michelson interferometer

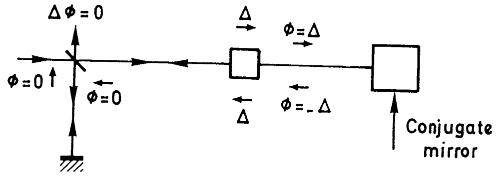

Fig. 5 Reciprocal perturbation on a conjugate mirror interferometer

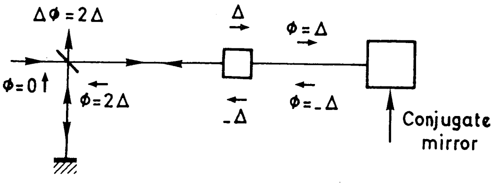

Fig. 6 Non-reciprocal perturbation on a conjugate mirror interferometer

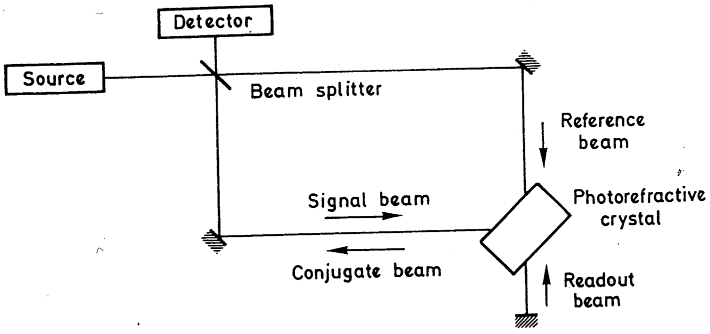

Fig. 7 Conjugate mirror Michelson interferometer

This is described in the following figures (figs. 8 to 11) (all phases are given with respect to the unperturbed configuration). If a reciprocal perturbation is placed on the signal arm, it is straightforward to see that the phase of the conjugate beam cancels exactly the phase variation due to the crossing of the perturbation on the return path, so that at the output, the phase of the conjugate beam is still equal to zero. On the other hand, in the case of a reciprocal phase perturbation placed on the reference path, the mechanism is the following.

After crossing the perturbation, the phase of the reference is Δ. Thus near the crystal, the various phases are

$$\phi_{\text{ref.}} = \Delta \ ,$$
$$\phi_{\text{readout}} = \Delta \ ,$$
$$\phi_{\text{signal}} = 0 \ ,$$
$$\phi_{\text{conj.}} = 2.\Delta \ .$$

After going through the perturbation, the readout's phase increases by Δ, and its value is 2Δ, so that at the output, the conjugate's and the readout's phases are equal and there is no change in the interference pattern. On the other hand, if the perturbation is non-reciprocal, it will cause a fringe shift at the output.

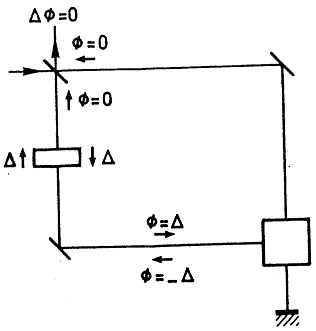

Fig. 8 Reciprocal perturbation on the signal arm

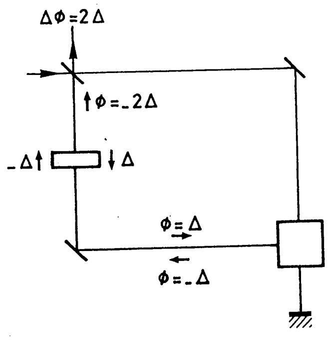

Fig. 9 Non reciprocal perturbation on the signal arm

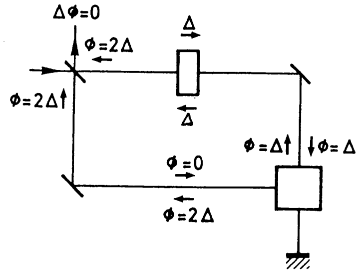

Fig. 10 Reciprocal perturbation on the reference arm

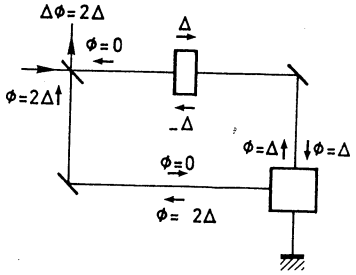

Fig. 11 Non reciprocal perturbation on the signal arm

III - PROPERTIES OF THE CONJUGATE MIRROR INTERFEROMETER

We have shown that the conjugate mirror interferometer is insensitive to reciprocal phase perturbations, and detects non-reciprocal perturbations. But this is in fact limited to phenomena which vary slowly with respect to the time constant of the crystal. The mechanism of the construction of the hologram involves the displacement of carriers in the crystal, and as these displacements are not instantaneous, the build-up takes some time, which can range from a few nanoseconds to a few minutes, depending on the material and the incident power [4,5]. This implies that the mechanisms we have just described are only valid for slowly varying phase perturbations. If the frequency of a perturbation is higher than the inverse of the response time of the crystal, the crystal only records the average of this signal, so that the conjugate beam's phase is the opposite of the average of the variable phase perturbation. Consequently, the output of the interferometer will detect the high frequency phase shift, while the D.C. component will be filtered out. This interferometer is then sensitive to varying phase signals or non-reciprocal phase signals, and ensures an automatic long term zero stability.

As a conclusion to this section we propose a scheme for a fiber interferometer using a conjugate mirror (fig. 12). The path of each arm is an optical fiber, which is monomode for the reference arm, and may be multi-

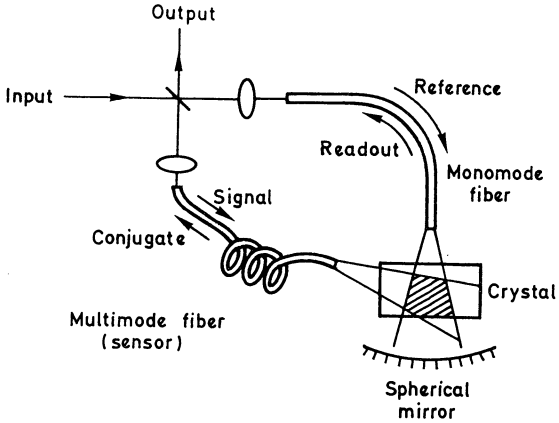

Fig. 12 Optical fiber Michelson interferometer

mode for the signal arm. As the reference beam is reflected back into the fiber with a spherical mirror, the reference fiber must be monomode to ensure reciprocity. But the signal beam is reflected by the conjugate mirror, and the wavefront of the return beam is exactly the same as that of the incident beam, so that even with a multimode fiber, the return path will be identical to the direct path, thus ensuring reciprocity. This interferometer has the same properties as the free wave conjugate mirror interferometer ; moreover, the multimode fiber on the signal arm can be used as a long interaction, low cost sensor for this interferometer.

IV - EXPERIMENTAL RESULTS

To demonstrate the conjugate mirror interferometer, we realized the setup represented in fig. 13. On one of the arms, we placed a cell in which we could change the air pressure from 1 to 5 atmospheres. This caused a change of the path length of about 10 λ. Because of the very low diffraction efficiency of the four wave mixing in the $Bi_{12}SiO_{20}$ crystal we used, we had to attenuate the readout beam by placing a $\lambda/4$ plate between the crystal and the mirror, and polarizers on the path of the readout beam and at the output of the interferometer.

This ensured maximum contrast of the fringes at the output. We used an argon laser at a wavelength of 514 nm, and with an output power of 100 mW.

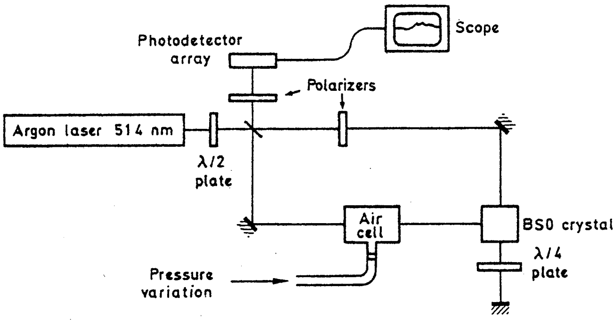

Fig. 13 Experimental setup

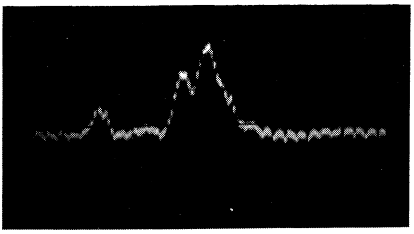

Fig.14. Output at one atmosphere

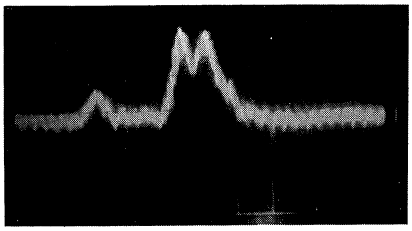

Fig.15. Superimposed outputs at 1 and 5 atmospheres

When we changed the pressure in the cell, we observed no change in the interference pattern, except a fast transient due to the settling of the modified hologram.

Fig. 14 shows the recording of the interference pattern at the output of the interferometer ; in fig. 15 there is a double exposition, the first one with a pressure of one atmosphere in the cell, and the second with a pressure of 5 atmospheres. The interference patterns are perfectly identical thus proving the feasability of the conjugate mirror Michelson interferometer.

We have demonstrated that the conjugate mirror Michelson interferometer is insensitive to slowly varying reciprocal phase variations on either arm, but detects both non-reciprocal or high frequency (with respect to the time response of the crystal) phase variations. The arms of the interferometer can either be free wave, or guided by optical fibers, one of which can be multimode.

References

[1] J.P. Huignard, J.P. Herriau, Appl. Opt. Vol 76 (77) p 1807

[2] J. Feinberg, R.W. Hellwarth, Opt. Lett. Vol 5 (80) p 512

[3] D.L. Staebler, J.J. Amodei, J. Appl. Phys. Vol 43 (72) p 1042

[4] J.O. White, M. Cronin Golomb, B. Fischer, A. Yariv, Appl. Phys. Lett. Vol 40 (82) p 450

[5] J.P. Herman, J.P. Huignard, J.P. Herriau, Opt. Lett. Vol 20 (81) p 2173

[6] T.J. Hall, M.A. Fiddy, H.S. Nar, Opt. Lett. Vol 5, 485 (1980)

[7] Ch. Bordê, Nato Advanced Study Institute on Quantum Optics and Experimental General Relativity - Bad Windsheim (1981)