LETTER TO THE EDITOR

Optical storage of information via refreshing by inverse seeding (OSIRIS)

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Abstract. In this paper we discuss the possibility for realizing an optical memory using dynamic refreshment. Via phase-correct back-coupling by means of nonlinear optical phase-conjugation the information stored in a photorefractive crystal is incessantly read out, transmitted into an auxiliary memory and from this back into the crystal again and in this way refreshed. Practical realizations and first results are presented.

1. Introduction

Optical information storage is one of the most interesting problems in the field of modern optics, especially, if the information is to be stored only temporarily and if after some time new data has to be written into the memory. Previous optical memories are either not eraseable (e.g. photographic plates) or preserve the information only for a limited and in some cases relatively short time (e.g. photorefractive crystals). Of course a memory is desirable that can store data and that can be erased at will, as well known in electronics. With that a possibility would exist for parallel storing [1]as well as reading [2] of two- or three-dimensional structures[3, 4], that means, to do this within only one step. Combined with some other arrangements for optical information processing, like filtering, datacompression, datareduction, arithmetical operating and so on[5], special parallel operations with large data amounts [6, 7, 8] are imaginable that have been reserved to very fast computers up to now [9].

Media that interact with light and thereby change their optical properties, like photorefractive crystals, are in principle utilizable as optical memories. Dependent on the mechanism of the interaction and on the material properties, the storage times are different and so either the information written in gets lost after this time or an irreversible process leads to an uneraseable storage.

In many fields of optics properties are desirable that allow storing for a free eligible time and that can be controlled by light. Like in electronics storage units using optical refreshment [11, 12, 13, 14] can be built that can store information for a desirable period [15] and furthermore change the stored information [16].

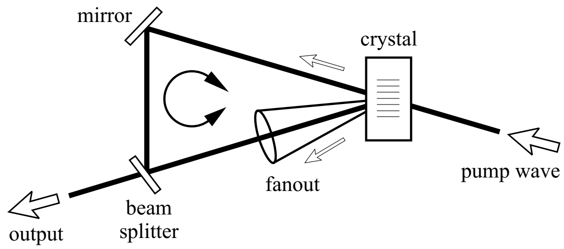

Figure 1. Arrangement realizing the back coupling of a wave.

2. Photorefractive Memory

If we limit ourselves to photorefractive crystals, the storing process is based on the Pockels effect. An interference pattern written into the photorefractive crystal by two waves with amplitudes $A_1(x, y)$ and $A_2(x, y)$ includes the information of both waves in the intensity distribution

$$I(x, y) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\phi(x, y)) .$$

The charge distribution formed by the spatially modulated illumination induces a modulation of the refractive index in the crystal and thus creates a so-called phase grating. If an other wave is diffracted at this phase grating the information can be read out. However, if one of the writing beams and with it the interference pattern describing the information is turned off, recombination and diffusion processes as well as the remaining illumination by the reading wave cause the charge contribution to homogenize, and thereby the refractive-index modulation fades away. That means that the information will be erased after some time. If we succeed in writing the information that is read out back correctly regarding the phase, it should be possible to keep the information in the crystal even if the signal wave is turned off. So, we have created an optical refresh-cycle.

3. Experimental Setups and Results

In order to investigate if our basic concept is correct a $BaTiO_3$ crystal was arranged in the setup shown in figure 1. The creation of a loop-shaped beam course makes it possible for the wave fanned in the crystal (fanout) and the pump wave to rotate clockwise and anticlockwise, respectively, and thereby to travel the same distance. So they interfere at their re-entry into the crystal and thereby they induce gratings. The incident pump wave is diffracted at this grating. The two-wave mixing process proceeding as a result and the back coupling by the loop cause a discrimination process that leads to an increasingly more directional fanning. A phase-conjugated wave is created, that can be varified using a semipermeable mirror. The setup corresponds to a SAGNAC-interferometer and represents a ring-resonator. In fact we could demonstrate this phase-conjugated wave for a wavelength of 514 nm as well as for 633 nm. The photorefractive medium was a

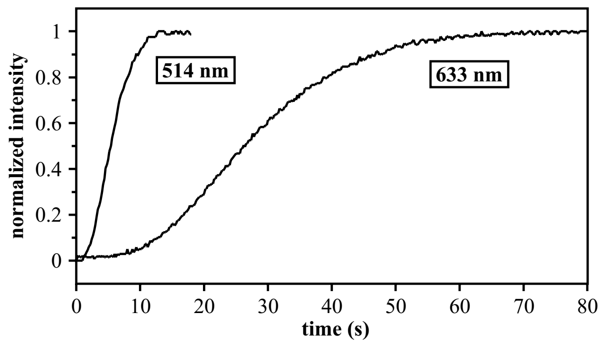

Figure 2. Intensity of the phase conjugated wave (output) as a function of time, measured with an Ar-laser ($\lambda = 514\,\mathrm{nm}$) and a HeNe-laser ($\lambda = 633\,\mathrm{nm}$), intensity for both wavelengths $10\,\mathrm{mW/mm^2}$.

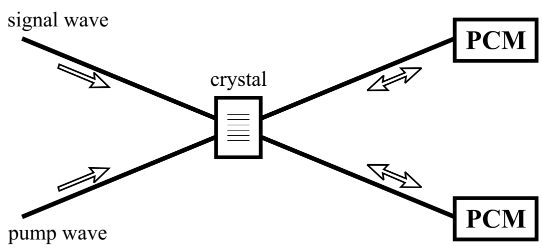

Figure 3. Optical arrangement for phase-correct reconstruction of gratings in a photorefractive crystal using PCM.

$BaTiO_3$-crystal with 45°-cut. Figure 2 shows the increase of the intensity of the phase conjugated wave with time for both wavelengths. Such ring-resonators are known from literature [9, 17], but, to our knowledge, have not been realized using a HeNe-Laser up to now.

Because photorefractive crystals can be used as gain media in ring-resonators, it should be possible to run them as so-called "Dynamic Optically Refreshable Stores" (DORS). However, it is necessary to keep the gratings correct regarding the phase of the two refreshing beams. The only possibility to realise this is to reflect both beams passing through the storage medium phase conjugated [5, 10], as shown schematically in figure 3. For this purpose it is necessary to use phase conjugate mirrors (PCM) with high reflectivities.

Since the reflectivity of self-pumped PCM is always lower then unity, the grating and with that the information stored in the crystal will fade away with time. A permanent storage would not be possible. In order to reach this goal we have to choose an arrangement that allows to couple back the amplified signal wave into the storage crystal [11]. Such an amplification can only be realized via four-wave mixing (FWM). Figure 4 shows the setup.

In a crystal X_1 the information S gets stored by interference with the pump wave P_1. After switching off the signal wave S the pump wave P_1 reads out the information.

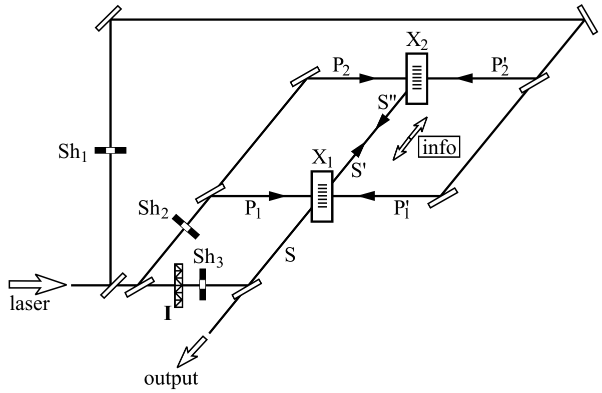

Figure 4. Memory setup using FWM for amplified feedback, X_1 and X_2 are $BaTiO_3$ crystals, Ar-laser with $\lambda = 514$ nm.

S is transferred to crystal X_2 as wave S'. This crystal is the active element of a FWM arrangement. As long as the wave exists it will interfere with the wave P_2 in crystal X_2 that works as an buffer-store for the information. The wave P_2' that is phase conjugated with respect to P_2 reads out the information stored in crystal X_2 by wave S'. So, the wave S'' is generated that is the phase conjugated wave with respect to S' and with correct chosen pump wave intensities it will be amplified with respect to S'. This wave is transferred to X_1 and interferes there with P_1' that is phase conjugated with respect to P_1. Thereby the initial gratings in X_1 are restored and so the original information is refreshed. The wave P_1 can be diffracted again at the grating and so S' is created and so on. The information to store oscillates between the two crystals X_1 and X_2, even if the signal wave is turned off by shutter Sh_3.

One Problem is that according to our investigations (and contrary to [17]) it is not possible to reach an amplification that is high enough in order to keep the device described above working by using the normal FWM arrangement continuously. The reason is that such an amplifying PCM needs a reading pump wave with an intensity that is much higher than the intensity of the signal wave. But because this pump wave is erasing as well as reading the gratings [18, 11], the reflectivity of the PCM will drop with time from a high value at the beginning to a low (steady-state) value at the end. In this case the writing by the signal and first pump wave would be as strong as the erasing by the second (reading) pump wave. Therefore we would like to use only the high reflektivity in the short time after switching on the reading pump wave. This is possible by a special shuttering. With suitable electronic shutters (Sh_1, Sh_2) the pump waves are controlled in such a way that they can be opened two at a time (P_1 and P_2 or P_1' and P_2') in order to write the information either in X_1 or in X_2. Figure 5 schematically shows the course of the refresh cycles

The gratings in crystal X_1 are written first by the waves S and P_1 and after one cycle by P_1' and S''. Both gratings have an identical shape because phase conjugation is used. Because the wave S'' is created by reading crystal X_2 by P_2' there can be a

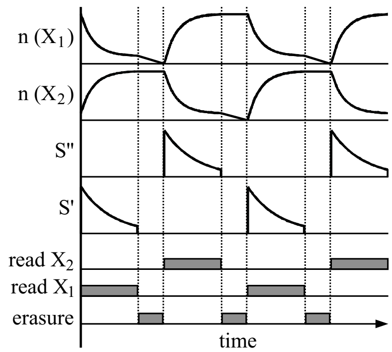

Figure 5. Course of the refresh cycles (schematically). Δn is the amplitude of the refractive index modulation and describes the strength of the grating.

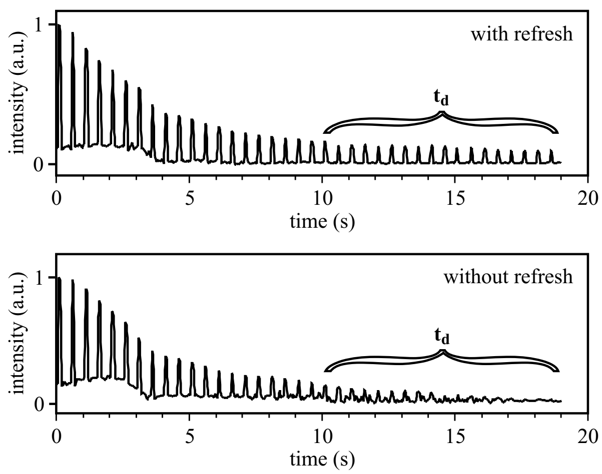

Figure 6. Comparison of the development of the output signal with time with and without refresh.

phase shift between original and refreshed grating that depends on the phase difference between the waves P_1' and P_2'. The same applies to the gratings in crystal X_2 where the phase shift between one grating and the grating that is written after passing the next cycle depends on the phase difference between the waves P_1 and P_2. So, there is an unavoidable gradual phase shift always between one grating and the following. This would lead to a superposition of shifted gratings inside each crystal and therefore after a certain number of cycles the gratings will be leveled and the information erased. In order to avoid this we introduced a procedure within each cycle (see figure 5) where the grating that has been read (and therefore already has been erased in some degree) will be erased completely by white light. That way, each time only one grating exists within one crystal and gradual erasure is avoided.

Figure 6 demonstrates the extension of the storage time reached with our setup compared with the storage time using one single crystal (only X_1) without back-coupling. Because you can only get an output signal if beams P_1' and P_2' are switched on (e.g. if Sh_1 is open), the graph is not a continuous curve, but looks like the shape shown.

We can proceed on the assumption that all output that occurs between any two opening periods of the shutter has nothing to do with the stored information. It is due to extra grating structures formed by the interference of other waves (fanout) into the crystal. One can regard these signals as a kind of noise and therefore one can only say that the signal is stored as long as the output during the opening periods of the shutter is clearly higher then between them.

At the beginning of the measurements the information that is simply read and that is read with refresh (back-coupling) show no or only small differences. Only after a time (about 10 s), that can be understood as the basic storage time of the medium, obvious differences occur. This observation time is called t_d in figure 6. The figure shows that for the back-coupling arrangement the pulse shape and the signal-to-noise ratio keep stable for a longer time than without refresh and this means that the information is stored longer. The output intensity decreases with time, but this has, of course only within reasonable limits, in principle no consequences for the application as an optical memory, especially, because one can see at figure 6 that the output intensity tends to reach a steady-state at a lower limit and to keep there for a longer time.

As information to be stored we have used a plane wave without a spatial amplitude modulation. So, we could store one Bit. As we see it, it should be possible to store a wave with spatial structure and with this to store larger amounts of data. This is suggested in figure 4 with the arrangement of a structured object ("**I**") in the path of the signal wave.

Photorefractive materials which enable strong interaction between light and medium and that therefore can be used for wave mixing often show disturbing effects as for instance beam fanning (mentioned above) what is a process that asymmetrically amplifies scattered light. This is especially important for barium titanate. Thus a noise background could build up in the storage arrangement that destroys the information. The influence of this noise is limited with our arrangement because we use a non-continuous resonator and erase all gratings in each crystal once in a cycle so that the noise is not as strong amplified. Nevertheless, some methods are known in order to avoid the appearance of fanning or reduce the influence of the fanned light on the signal that is handled. These methods use for instance the different response times of fanning and regular gratings [19, 20] what can advantageously be used with our setup if the read times are choosen to be shorter than the response time of the fanning. Furthermore, different intensity dependencies [21, 22], special positioning of the crystals [23] and threshold filtering [24, 25] could be applied with our setup. Another possibility is incoherent erasure [23, 26, 27, 28]. With this method the initially weak fanning gratings can be erased nearly without influencing the stored information and further amplification of the noise can be avoided. The mentioned techniques are not yet applied for our measurements shown in figure 6. Corresponding experiments and tests for the storage of real images are in progress.

4. Conclusion

We have presented an idea for realizing a dynamic optical memory that uses phase conjugation in order to build a refresh-cycle. The infomation is not stored statically but oscillates between the main memory and an auxillary memory. This method combines the advantages of the holographic information storage with those of a writeable, readable and eraseable memory. Some principal considerations regarding the possibility to store information in a dynamic loop have been shown. We have suggested and tested a memory setup that is based on our idea, and we could demonstrate that an extension of the storing time can be reached with it.

References

[1] Curtis K, Pu A, and Psaltis D 1994 *Opt. Lett.* **19** 993
[2] McMichael I, Christian W, Pletcher D, Chang TY, Hong JH 1996 *Appl. Opt.* **35** 2375
[3] Kawata Y, Ueki H, Hashimoto Y, Kawata S 1995 *Appl. Opt.* **34** 4105
[4] Ueki H, Kawata Y, Kawata S 1996 *Appl. Opt.* **35** 2457
[5] Kang H, Yang C X, Mu G G, Wu Z K 1990 *Opt. Lett.* **15** 637
[6] Barbastathis G, Psaltis D 1996 *Opt. Lett.* **21** 432
[7] Campbell S, Yeh P 1996 *Appl. Opt.* **35** 2380
[8] Mok F H 1993 *Opt. Lett.* **18** 915
[9] Anderson D Z, Erie M C 1987 *Opt. Eng.* **26** 434
[10] Drolet J J P, Chuang E, Barbastathis G, Psaltis D 1997 *Opt. Lett.* **22** 552
[11] Denz C, Dellwig T, Rauch T, Tschudi T 1995 proc. "Photorefractive Materials, Effects and Devices" Aspen (Colorado) USA 291
[12] Dellwig T, Denz C, Rauch T, Tschudi T 1995 *Opt. Commun.* **119** 333
[13] Sasaki H, Fainman Y, Ford J E, Taketomi Y, Lee S H 1991 *Opt. Lett.* **16** 1874
[14] Brady D, Hsu K, Psaltis D 1990 *Opt. Lett.* **15** 817
[15] Lande D, Orlov S S, Akella A, Hesselink L, Neurgaonkar R R 1997 *Opt. Lett.* **22** 1722
[16] Boj S, Pauliat G, Roosen G 1992 *Opt. Lett.* **17** 438
[17] Klumb H, Herden A, Kobialka T, Laeri F, Tschudi T, Albers J 1988 *J. Opt. Soc. Am.* B **5** 2379
[18] Agranat A, Yacoby Y 1988 *J. Opt. Soc. Am.* B **5** 1792
[19] Rajbenbach H, Delboulbe A, Huignard J P 1989 *Opt. Lett.* **14** 1275
[20] Zhang G, Liu S, Tian G, Xu J, Sun Q, Zhang G 1997 *Appl. Opt.* **36** 1815
[21] Joseph J, Pillai P K C, Singh K 1990 *Opt. Commun.* **80** 84
[22] Joseph J, Pillai P K C, Singh K 1991 *Appl. Opt.* **30** 3315
[23] Breugnot S, Rajbenbach H, Defour M, Huignard J-P 1995 *Opt. Lett.* **20** 447
[24] Khoury J, Woods C L, Cronin-Golomb M 1991 *Opt. Lett.* **16** 747
[25] Fu J, Khoury J, Cronin-Golomb M, Woods C L 1995 *Appl. Opt.* **34** 346
[26] Byron Q, Yeh P 1994 *Appl. Opt.* **33** 283
[27] Kawata Y, Kawata S 1993 *Appl. Opt.* **32** 730
[28] Gu C, Sornat G, Hong J 1996 *Opt. Lett.* **21** 1070