Characteristics of Optical Interconnection for Power Transmission Based on Phase Conjugation Generation by a Ring-Resonator

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To establish an interconnection for power transmission between two moving objects, optical phase conjugation is applied for non-mechanical, all-optical tracking and compensation of atmospheric distortions. The installation of the connection starts in sending a coherent pilot signal by the power receiver towards the transmitter. There, the incident light is collected and directed into a nonlinear medium placed inside a ring cavity. Scattered light enters the resonator and initiates a dynamic hologram writing with the incident pilot signal. Hence, a stable oscillation is generated by diffracted light of the pilot signal.

Out-coupling is performed by a combination of an in-cavity half-wave plate and a polarizing beam splitter. This beam is reflected back into the nonlinear medium to generate the phase conjugated beam by four-wave mixing. Phase and direction of this beam can be manipulated without affecting the dynamic hologram thanks to the previous performed out-coupling. The final power transmission is realized by amplification of the phase conjugated beam.

In this paper, we present initial results of the described setup. The angular range of generating the phase conjugated beam and its fidelity is analyzed.

Key Words: Laser Power Transmission, Optical Interconnection, Phase Conjugation

1. Introduction

Optical free space interconnections between moving objects in space are considered for communication and power transmission purposes. Laser applications for communication in space are attractive because of increased data rates and power transmission for more flexible exploration missions like remote powered planetary rovers on moon or mars in the future. Furthermore, satellites are thought to be powered during their earth eclipse or transfer orbits by laser beams. Especialy for interconnections with the purpose of power transmission, precise and reliable tracking is required to constantly supply the target with energy.

Beam steering is so far realized mechanically. Tracking is made by spatially modulating the laser beam so that by detecting reflected light from the target provides information about the target's movement. An electronic feedback control loop then calculates the correction.

A different way represents an all-optical tracking including compensation of phase front distortions by a phase conjugated mirror (PCM). A coherent pilot signal is emitted from the receiver and collected at the transmitter. Its phase conjugated beam is generated by the PCM before amplification is conducted to enhance the reflectivity. It propagates back and automatically tracks the target. For the system described in this paper, multiple PCM's are proposed in order to increase the aperture of the transmitter. In that way, tracking over larger angles with better focus can be achieved.

In this paper, we describe and test a unique phase conjugator for this purpose. A photoactive ring resonator is pumped by the incident signal beam and the out-coupled beam generates the phase conjugated beam by four wave mixing. This flexible setup thus allows to control the phase and to adjust the direction of the phase conjugated beam. The latter is crucial in case of insufficient response time of the conjugation process and for compensation of time-of-flight delays between the moving objects as for instance satellites.

2. Optical Retro-Directive Interconnection

2.1 Interconnection by an array of Phase Conjugate Mirrors

The design of the aimed system is shown in Fig. 1. It consists of two objects, the data/power receiver (referred as A) and its transmitter (B). The installation of the interconnection starts by sending a coherent pilot beam from receiver A towards transmitter B which consists of N single transmitter elements. Each is actively phase controlled to form a phased array. The direction and phase front distribution of a single element's emitted beam is determined by the PCM. Its power and phase conjugate reflectivity is increased by an...
additional amplifier so that the PCM’s reflectivity is expressed by:

\[ R = \frac{P_{\text{out}}}{P_{\text{inc}}} = \frac{R_{\text{PCM}} \cdot P_{\text{inc}} \cdot g_A^2}{P_{\text{inc}}} = R_{\text{PCM}} \cdot g_A^2 \]  

(1),

where \( P_{\text{inc}} \) and \( P_{\text{out}} \) are the incident and output power, \( g_A \) the gain of the amplifier and \( R_{\text{PCM}} \) the reflectivity of the pure PCM. The incident power \( P_{\text{inc}} \) is approximately given by

\[ I_{\text{inc}} = \frac{P_{\text{in}}}{\pi s^2 \theta_{\text{div}}} \]  

(2),

where \( P_{\text{in}} \) is the power of the signal laser at A, \( \theta_{\text{div}} \) the pilot laser’s half width divergence angle. The nonlinear intensity profile of the signal laser is neglected in this formula.

The incident wave at B can be assumed to be a plane wave if its curvature \( R(s) \) at B is sufficiently flat and the aperture \( A_{\text{trans}} \) small against the spot of the signal laser after propagation over distance \( s \):

\[ A_{\text{trans}} \ll R_{\text{SL}}(s) \cdot \theta_{\text{div}} \]  

(3).

Therefore, the phase conjugated beam can also be treated as a plane wave.

By assuming long distance transmission \( s >> \pi A^2/\lambda \) (\( \lambda \): wavelength of the used light), Fraunhofer diffraction is observed and a single beam is thus diffracted to an airy distribution.

The spot size \( S_{\text{sec}} \) at the receiver is given by the Airy Disk \( S_{\text{sec}} = 2.44 s/\lambda b \). The spot size can be strongly decreased and therefore increased by constructive interference of the N elements of the transmitter array. For \( FF = 1 \), \( I(0) \) will be increased \( N^2 \) times while \( S_{\text{sec}} \) is reduced to \( S_{\text{sec}}/N \). The intensity distribution is given by the formula for multiple beam interference.

### 2.2. Single element phase conjugator design

The design of a phase conjugator as a single array element is shown in Fig. 2. The signal beam (B1) hits an optical nonlinear crystal (NLC) which is placed inside a resonator which is formed by a polarizing beam splitter PBS and mirrors M1 to M3. Scattered light hits the nonlinear crystal (beam B2). Scattered light enters the resonator through occurring beam fanning and hits the nonlinear crystal (beam B2). Assuming the laser’s coherence length being longer than the cavity’s, these mutual coherent beams write a Bragg grating by refraction index modulation inside the crystal by the occurring Pockel’s effect. In that way, B1 gets diffracted into the resonator and amplifies B2.

Scattered light is amplified by two-wave mixing between scattered light and the incident beam B1 during beam fanning. It can be written as:

\[ I_s(\theta_2) = I_s(\theta_1)e^{\left(\alpha L\right)} \]  

(4),

where \( I_{s0} \) is the initial scattered light intensity into angle \( \theta_1 \).

The resulting oscillation condition for the sensitivity threshold of the used material can be expressed by:

\[ I_{\text{osc}} < I_s(\theta_2) = I_s(\theta_1)e^{\left(\alpha L\right)} \]  

(5),

where \( I_{\text{osc}} \) is the sensitivity of the material.

The oscillation condition for a photorefractive ring resonator is given by:

\[ \gamma L > \gamma_0 L := \alpha L - \ln R \]  

(6),

where \( \alpha \) is the absorption coefficient, \( \gamma \) the coupling constant of the nonlinear crystal, \( L \) the interaction length of B1 with B2 and \( R \) the reflection coefficient of the empty resonator. The coupling constant \( \gamma \) is given by:

\[ \gamma = \frac{2n_L}{\lambda \cos \theta} \cos \phi \]  

(7),

where \( n_L \) is the refraction index modulation, \( \theta \) the Bragg angle and \( \phi \) the phase of the interference pattern between B1 and B2.

Generally, there will be a slight detuning \( \Omega \neq \Omega_0 \) because of the resonator’s boundary condition that the oscillating beam’s wavelength can only be a multiple of the resonator’s length. Especially for fast processes, this to be considered but in case of a photorefractive crystal with response times typically in the order of \( \tau = 0.1 \text{ s} \), a frequency shift of only about \( \Omega \sim 1 \text{ Hz} \) is occurring which is usually below the used laser’s bandwidth (~MHz) so that many longitudinal modes of the resonator can be supported.

Two amplifiers are implemented to support this process and to finally achieve a high reflectivity. The first amplifier AMP1 pre-amplifies B1 before hitting the crystal and AMP2 facilitates the oscillation condition. Out-coupling is controlled by a \( \lambda/2 \) plate in combination with the PBS. The out-coupled beam is reflected by a spatial light modulator and re-enters the resonator. The reflected beam (B3) is then co-parallel to B2 so that four wave mixing occurs. This generates B1’s phase conjugated beam B4.

The \( \lambda/2 \) plate with angle \( \phi_0 = \phi \) to the horizontal plane turns the polarization angle by \( 2\phi \). The amount of out-coupled light is therefore \( P_{\text{out}} = P_{\text{osc}} \cdot \cos^2(2\phi) \). The amount of out-coupled power of light in the resonator.

Amplifiers AMP1 and AMP2 are set that B1 and B2 have approximately the same intensities in the crystal providing a maximum visibility of the interference fringes inside the crystal. So they write a deeper refractive index grating with modulation \( n_L \). Hence, the maximum diffraction efficiency from B3 to B4 is achieved. Non-diffraction light will get absorbed by a non-reciprocal element NREL for light beams to ensure one-way oscillation only within the resonator.

Finally, B4 gets amplified by AMP2 and should now be stronger than \( P_{\text{in}} \) on the receiver A to have an effective power transmission from B to A (Fig. 1).

### 3. Experimental Setup and Results

Since an initial setup for observing multiple beam interference of one speed signal beam’s phase conjugated beams has been already tested before,9,10 we are examining at this point an optical setup which is similar to the design of the described phase conjugator in chapter 2.2. The setup is shown in Fig. 3.
The setup differs in the number of mirrors. Here, only 3 mirrors were used to form the cavity. 2 of them were concave mirrors (f=500 mm) while M1 was a plane dielectric mirror with R > 0.99 for λ=532 nm.

The legs of the triangle were set to \(a = b = 10 \pm 1 \text{ cm}\) so that \(c = 15 \pm 1 \text{ cm}\) having \(\xi = 90^\circ\) and \(\zeta = \chi = 45^\circ\). The reason for changing the setup was mainly geometrical. The used PBS only works efficiently, if light is incident 45° to the splitter edge and M1 specified to be only efficient until \(\gamma = 90^\circ\). For obtaining smaller angles \(\alpha\) and \(\beta\), a triangular shape is favoured. However, the principle of operation in this setup remains the same.

Two Co-doped Sr\(_x\)Ba\(_{1-x}\)Nb\(_2\)O\(_6\) (Co:SBN) crystals of size 2x5x6 mm were available where the 5x6 mm sides was the only polished one. The crystal was put onto the 2x6mm plane so that the axis of highest nonlinearity was orientated horizontally. Characteristics as the response time and the angular dependence of the coupling constant of these crystals were studied already before.\(^{11}\)

Incident light was linearly P-polarized which was transferred to the oscillating beam B2. An angle of the half wave plate between \(\phi/2 = 0^\circ\) and \(\phi/2 = 45^\circ\) has to be found as a compromise between resonator oscillation and phase conjugation reflectivity. A small angle \(\phi/2\) supports the oscillation but doesn’t provide a high power for B3 while an angle close to \(\phi/2 = 45^\circ\) results in a cease of oscillation since all the light gets reflected by the PBS to become beam B3. This behaviour for SBN-crystals can be in general different for other photorefractive crystals.

As laser source, we used a frequency doubled single longitudinal mode emitting Nd:YAG laser in continuous wave operation at 532nm (CrystaLaser, NV, USA). The nominal output power of this model is 150mW.

### 3.1. Experimental Results

At first, stable multi-transversal electromagnetic mode oscillation could be observed by illuminating the nonlinear crystal with the laser beam with power of several mW. Then, the diameter of the pinhole PH was reduced to limit the transversal mode orders with the result that a single TEM\(_{00}\) mode could be observed, but only in an unstable operation.

By turning the half-wave plate, the amount of out-coupled light could be controlled until a certain angle where losses in the resonator became too big and oscillation ceased. With a precise adjustment of mirror M2, phase conjugation could be achieved with high fidelity.

Table 1 shows the measured power of the phase conjugated beam on screen \(\Sigma\). The incident power of beam B1 on the crystal was \(P(0) = 30\) mW. It shows that this setup is able to provide phase conjugation over a large angular range. Angles smaller than \(20 = 20^\circ\) could not be measured with this initial setup since optical elements blocked the beam path. On the other hand, phase conjugate reflectivity is very small. We expect that it will be strongly increased after the implementation of the two amplifiers shown in Fig. 2.

The angle of the half wave plate \(\phi/2\) could be set up to about 20° before the oscillation in the resonator ceased.

Turning mirror M2 with a stepper motor, the direction of B3 was varied (see Fig. 4). In Fig. 5, pictures (a) until (n) show the beam’s shape steered over a total angular range of 2 mrad. A picture of the signal beam B1 is included as picture (o) which was taken at a distance equal to the length BS-\(\Sigma\) in front of BS for correct comparison.

To quantify the degree of fidelity \(F\), the pictures were analysed by using the following correlation integral:\(^{12}\)

\[
F = \frac{\int\int |E_\Sigma(r)E_p(r)|^2 \, dr \, dy}{\int\int |E_\Sigma(r)|^2 \, dr \, dy \int\int |E_p(r)|^2 \, dr \, dy} \quad (8)
\]

\(E_\Sigma\) and \(E_p\) are the electrical field amplitudes of the signal.

Table 1  Initial results of the phase conjugated beam’s power on screen \(\Sigma\) \((P(\Sigma))\) as a function of the angle of incidence 2\(\theta\). Shown as well, the half wave plate angle \(\phi/2\).

<table>
<thead>
<tr>
<th>(\theta)</th>
<th>(P(\Sigma))</th>
<th>(\phi/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td>2.8 µW</td>
<td>18°</td>
</tr>
<tr>
<td>25°</td>
<td>1.0 µW</td>
<td>20°</td>
</tr>
<tr>
<td>30°</td>
<td>2.8 µW</td>
<td>17°</td>
</tr>
<tr>
<td>35°</td>
<td>1.0 µW</td>
<td>20°</td>
</tr>
<tr>
<td>40°</td>
<td>0.3 µW</td>
<td>11°</td>
</tr>
<tr>
<td>45°</td>
<td>0.007 µW</td>
<td>10°</td>
</tr>
</tbody>
</table>

![Fig. 3 Experimental setup for testing the phase conjugator using a ring resonator.](image-url)

![Fig. 4 Optical setup for examination of the phase conjugate fidelity as a function the beam alignment.](image-url)
and phase conjugated beam. Both field amplitudes were normalized during the calculation process. Fig. 6 shows the results.

The difference from the highest value $F = 0.96$ to perfect fidelity can be supposed originating from distortions by optical elements. A plateau is observed at $F = 0.94$ over a span of about $\pm 0.5$ mrad. By comparison with the pictures in Fig. 5, we can conclude that all values above $F = 0.93$ (indicated by the dotted line) are useful for steering applications since the distortions are not too strong.

The resonator couldn’t provide stable TEM$_{00}$-operation, so we were not able to compare these data to intensity measurements which were carried out before with a standard four-wave mixing setup. However, the obtained fidelity graph behaves less stringent to beam steering as the decrease of reflectivity.

4. Conclusion

To realize the optical interconnection by phase conjugation described in chapter 2, we built and examined a phase conjugator in a ring cavity. Stable multi-transversal electromagnetic mode and unstable single TEM$_{00}$ oscillation could be observed in the ring resonator and phase conjugation with high fidelity was generated. Since the phase conjugated beam's power dependence on the angle of misalignment in the four wave mixing setup was studied before, we measured the degradation of the fidelity in this study. The data revealed that fidelity is stable until a critical angle. So it can be concluded that a certain angular range exists in where the phase conjugated beam can be steered without significant loss of phase conjugation fidelity. This is important for optical interconnections between fast objects to compensate any time delays during the generation process by steering.

To proceed further in realizing the interconnection for power transmission, amplifiers will be implemented into the setup. Furthermore, different nonlinear materials such as polymer dyes or lasing media will be tested for better sensitivity and response time.

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References