Second-Harmonic Vortex Generation with a Poled Glass

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Abstract: A Simple method for nonlinear vortex generation is presented. Spin-to-Orbital transfer with total angular momentum conservation between photons at the fundamental and at the second-harmonic frequency is demonstrated.
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1. Introduction

Optical vortex beams are characterized by a wave-front dislocation where the electric-field is not defined and the phase spirals around the singularity in the electromagnetic field. The special properties of such beams associated with their orbital angular momentum allow for useful applications such as the exchange of angular momentum between light and matter and optical tweezers [1]. Spin-to-orbital conversion promises new avenues for quantum computation [2]. However, the decomposition of the light total angular momentum into a spin part (SAM) and orbital part (OAM) is still very much debated especially in the non-paraxial approximation [3]. Spin-to-orbital transfer in nonlinear parametric vortex generation provides an interesting test for the conservation law of the total momentum between photons at the fundamental and harmonic waves.

In sharp contrast to the complexities associated with vortex generation by linear methods we present in this work a simple nonlinear method for vortex generation. We show that the interaction between a Gaussian circularly polarized IR beam with a silica glass plate containing an embedded DC-field (poled glass) results in the material being modified in 3-dimensions by the beam itself. The process is modeled in the framework of electric-field induced second-harmonic (EFISH). Generation of circularly polarized second-harmonic (SH) vortex of topological charge 1 is predicted and experimentally confirmed by revealing the single-branched phase spiral through interference. The total angular momentum is conserved through the process and spin-to-orbital transfer from the photons at the fundamental wave to the SH photons is observed.

2. Experimental methods and Results

The process known under the name of “glass poling” allows freezing a DC-field in the bulk of glass. A 22 x 22 x 1 mm^3 fused silica glass plate (Vitrosil) is brought to 280 ^oC while simultaneously applying 4 kV across it via a pair of silicon electrodes for 25 minutes. Under the action of the external field, impurity ions (Na^+) drift away from the anode leaving behind a negatively charged uniform region constituted by Si-O^- non-bridging oxygen hole centers. As a result an electric field develops between this region and the anode. The charges are then immobilized in their new sites by cooling the glass to room temperature thus freezing the uniform field (E_{dc}). Since the region depleted of charge carriers extends for approximately 4 μm and 4 kV were applied E_{dc} is in the range of 10^9 V/m. This value is sufficient to give rise to second order nonlinear effects. In fact the $\chi^{(2)}$ estimated via $\chi^{(2)} = 3\,\chi^{(3)}\,E_{dc} \sim 0.6$ pm/V. (See for example $\chi^{(2)}_{LBO} = 2.2$ pm/V).

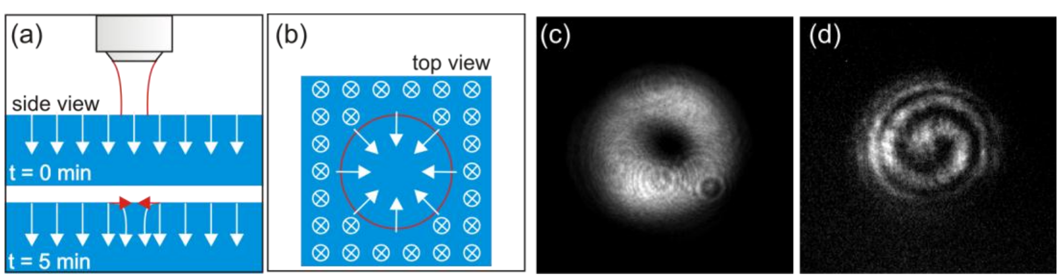

Figure 1 (a) schematic of the experimental layout with an IR Gaussian beam focused on the surface of a poled glass plate with an embedded uniform DC-field (E_{dc}). Multi-photon absorption causes erasure and redistribution of E_{dc} with the appearance of field components parallel to the surface. (b) Top view of the modified glass plate with radially distributed field lines. After 5 minutes of exposure the singularity in E_{dc} is fully established and (c) a well-defined circularly polarized SH vortex is generated. (d) The single-branch spiral obtained via interference indicates that the vortex has topological charge 1.

Light itself is exploited to manipulate the 3-dimensional spatial distribution of E_{dc} . The circularly polarized laser beam of a Nd:YVO_4 laser delivering 8 ps pulses at the wavelength of 1064 nm at 200 kHz is focused via a ×10 objective (NA = 0.25) on the surface of the glass specimen. The peak intensity is 4×10^{12} W/cm^2. At such intensities the electrons stored in the Si-O$^-$ defects are ionized by multi-photon absorption and travel along the electrostatic field to eventually locally screened it. In response to the removal of charges the electrostatic field redistributes itself giving rise to components of the field parallel to the glass surface and directed radially towards the centre of the beam (Fig.1b).

The components of E_{dc} parallel to the surface are responsible for SHG. The formation of the singularity in the SH wave-front can be intuitively understood considering that SH light beams produced through the coupling with DC fields of opposite directions are π-out of phase. Therefore in the centre of the singularity the SH electric-field must go to zero. Incident circular polarization gives origin to a so-called "doughnut" beam (Fig. 1c). The SH beam preserves the circular polarization of the fundamental beam as tested by analyzing the SH beam with a linear polarizer and observing that its characteristic intensity distribution is not modified. The beam is in fact an optical vortex. We proved it by de-focusing the pump beam so that the SH vortex is made to interfere with the SH generated by the coupling of the non-paraxial converging IR photons with the E_{dc} components perpendicular to the glass surface. A single-branch spiral is produced indicating that a vortex of charge 1 is formed (Fig. 1d). The results match well with numerical predictions based on the formalism of EFISH (Fig. 2).

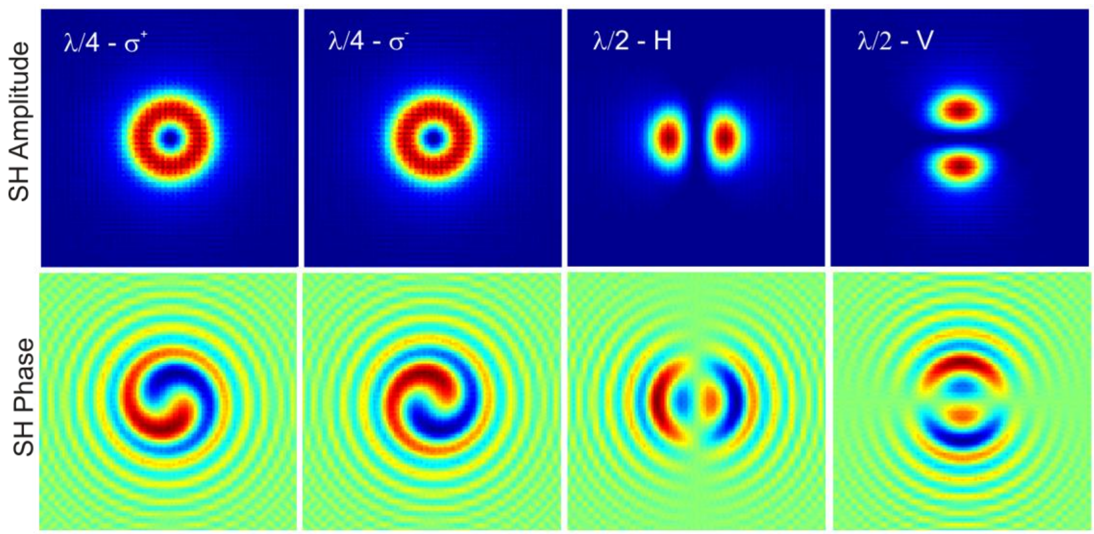

Figure 2 Nonlinear vortex generation is modeled via the formalism of EFISH and solving the coupled mode equations for the complex amplitude of the SH field as it travels through the nonlinear medium assumed of 4 μm thickness. The fundamental is taken as a plane wave with Gaussian intensity distribution. Amplitude and phase are retrieved for both circular and linear polarization of the fundamental beam

This experiment suggests that spin-to-orbital conversion in second-order nonlinear processes requires total conservation of momentum. In the parametric process of SH generation two photons at frequency ω combine to create one photon at frequency 2ω. Energy conservation is expressed by $2\hbar\omega = \hbar\omega + \hbar\omega$. Total angular momentum conservation is expressed as $(1 + 1)[SAM_{2\omega} + OAM_{2\omega}] = (1 + 0)\,[SAM_{\omega} + OAM_{\omega}] + (1 + 0)\,[SAM_{\omega} + OAM_{\omega}]$.

In conclusion a simple all-optical method for the nonlinear generation of optical vorteces is demonstrated and applied to the study of spin-to-orbital transfer in second-harmonic generation where the pump beam does not carry OAM. The creation of 2D arrays of topological singularities in E_{dc} is foreseen by the same method.

3. References

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