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Thermal Poling of Fibers with Multi-anodes

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Abstract: We demonstrate thermal poling of fibers with ~50 and ~500 anodes. The second order nonlinearity layers are developed surrounding all the rings of wires in the ~50 anode fiber and the outer rings of the ~500 anode fiber.

OCIS codes: (190.4160) Multiharmonic generation; (190.4370) Nonlinear optics, fibers; (190.4400) Nonlinear optics, materials; (160.3918) Metamaterials.

1. Introduction

Thermal poling can break macroscopic centrosymmetry of silica glasses and create second-order nonlinearity (SON), $\chi^{(2)}$, in glasses and waveguides. The mechanism is generally considered to be the migration of mobile charges, which are driven by the electric field at elevated temperature. However, in the two-anode poled twin-hole fibers, when the two electrodes are at the same positive voltage, a counterintuitive observation was obtained that a much stronger and temperature stable SON layer was created between the two anodes [1, 2]. While the electric field should be small between the two anodes when the same potential is applied, an avalanche-like positive feedback mechanism happens during the two-anode poling process [1]. As fibers can accommodate more holes and thus, more electrodes, it is interesting to explore how far this thermal poling can be extended from just two anodes, and the extent to which an induced SON can be distributed through the volume of the glass. Poling these structures and inducing a SON may enable tunable metamaterials [3] with potential applications in sub-diffraction imaging and waveguide devices. In this paper, we demonstrate experimentally thermal poling of fibers with ~50 and ~500 tin wire array anodes, arranged in concentric rings. SON layers are created surrounding the wires. Simulations of the thermal poling process based on a two-dimensional charge dynamics model [4,5] are conducted to illuminate the physical mechanism involved.

2. Fabrication and thermal poling of multi-wire array optical fiber

The wire array metamaterial fibers based on glass and tin are fabricated by the stack and draw technique. The glass is AR-GLAS from Schott and its chemical composition in weight is: SiO₂(69%), B₂O₃(1%), K₂O(3%), Al₂O₃(4%), Na₂O(13%), BaO(2%), CaO(5%), MgO(3%). The diameter of the fiber and the tin filled holes are ~1000 μ m, and ~10 μ m, respectively, and the pitch of the tin filled holes is ~20 μ m. During poling the fibers are placed on an electrically grounded hotplate at high temperature. To avoid thermal runaway and dielectric breakdown, the poling voltage is increased from 500V to 1.8kV with a step of 100V every 2min. 1.8kV DC voltage is applied to the tungsten wire for 30min. The ~50 and ~500 wire fibers were poled at 210°C, and a second ~50 wire fiber was poled at 250°C for comparison. After poling, the samples are cooled down to room temperature before the voltage was switched off. The poled samples were characterized using second harmonic (SH) microscopy [6]. The resolution was estimated to be ~0.4 μ m.

Typical SH microscope images of the ~50 wire fiber poled at 1.8kV, 210°C for a duration of 30min are shown in Fig. 1. Figure 1(a) shows that SH signals were found in rings around most of the holes. Several holes are not well poled, presumably due to poor connection of the wires. SH signals were clearly enhanced when poled at higher temperature, as shown in Fig. 1 (b). The intensities of the SH signals in Fig. 1 (b) are comparable to those observed in poled silica fiber. Note that since y-polarized light is used in the SH microscopy, the observed SH signals are strong along the y-direction while weak along the x-direction. For the poled ~500 wire fiber at 210°C, 1.8kV and 30min duration (not shown here) the SH signals are induced in the glass proximal to the wires making up the outer rings of wires with intensity stronger than the results in Fig. 1(a) but lower than that in Fig. 1(b).

The results show that the SH signals are generated just underneath the surface of the holes, and after a poling period of 30 min they have a width of ~1 μ m. This observation, combined with the strong dependency of SH intensity on poling temperature, is consistent with the accepted mechanism of poling (rather than perhaps being due to polarization in the metal glass interface). More specifically we can conclude that the alkali metal ions are the dominant charges migrating during poling. The enhancement of the SH signal intensity at higher temperature is also consistent with short poling duration results, during which the depletion region is formed gradually, and the migration of the following second kind of mobile charges can be neglected.

The results shown in Fig. 1 are apparently quite anomalous, because if all the wires are at the same potential it might be expected that the outer ring of wires would effectively screen the inner wires and there would be no field within this ring, and just radial fields from the outer ring. This observed pattern however can be explained by referring to the avalanche-like positive feedback mechanism [1] or the similar “self-adjustment” mechanism [2]. The migration of charges starts from the outer wire rings, where the strength of the electric field is initially relatively strong, this process creates local depletion regions in which the resistivity is very high. This in turn causes a modification of the electric field distribution around the inner rings, and promotes the migration of charges in the inner rings. Our simulation based on two dimensional charge dynamics model confirms the self-adjustment mechanism, and shows the SON layers are induced from the outer rings to the inner rings.

Fig. 1. SH signals of the ~50 wire array anode poled fiber (a) at 210°C, 1.8kV for 30min and (b) at 250°C, 1.8kV for 30min. Note that the tin (melting temperature ~232°C,) is liquid at poling temperature 250°C, potentially improving the continuity of the tin wires in the fiber.

3. Conclusion

In conclusion, we demonstrate experimentally poling ~50 and ~500 tin wire array fiber. The results show the ~50 wire fibers are successfully poled such that all rings of wires develop SON layers, and the SON increases with increased poling temperature. SON layers were also observed surrounding the outer rings of wires in the ~500 wire fiber poled at lower poling temperature. Our simulation based on a two-dimensional charge dynamics model reveals the charge migration process in the multi-wire fiber. Although there is initially no electric potential drop in the inner wire rings, which would prevent charge migration in this region, the SON layers develop at the outer rings of wire at first, then the inner rings, and finally all wires are surrounded by an induced SON layer after sufficiently long poling time. This is consistent with the self-adjustment mechanism in a two-anode poled fiber.

The findings extend poling of fiber from two anodes to multi anodes. Poled multi-wire fiber can be potentially applied for electro-optic modulation or frequency conversion, even a QPM structure may be obtained by using the multi-wire glass material from the side if the wires are removed. In addition, these results may also open up possibilities for tunable metamaterials.

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