New Prospects for Poled Fiber Technology in Frequency Doubling and Sensing

Simon Fleming, Honglin An, Andrew Michie
Institute of Photonics and Optical Science, School of Physics, University of Sydney, NSW 2006, Australia
s.fleming@usyd.edu.au

Abstract: Second order nonlinearity can be created in silica fibre by poling. Practical electro-optic switches have been elusive. This paper describes new developments demonstrating real prospects for applications in sensing and second harmonic generation.

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1. Introduction

Silica optical fiber has underpinned the photonics telecommunications revolution, largely because of its properties of low loss, robustness, low nonlinearity etc. are nearly ideal for transmission. Rare earth doping and photosensitivity have extended its capabilities by adding extra functionality. However its lack of Linear Electro-Optic (LEO) behaviour and Second Order Nonlinearity (SON) prohibits functionality such as electro-optic switching or Second Harmonic Generation (SHG) which would be valuable for some important applications, which are currently served by expensive nonlinear crystals such as lithium niobate.

The technique of poling has been developed to break the symmetry of the glass and induce a non-zero SON. [1] This technique typically involves applying a large electric field across the core of the fibre whilst it is heated. The technique can repeatably induce a modest SON and this has been used to develop impressive electro-optic switches suitable for telecommunications applications. [2. However poled fibre devices have not made any significant practical impact in this area, presumably because the induced SON is relatively modest, being one to two orders of magnitude smaller than that of crystal devices.

Optical fibre however has a number of very important differences from these nonlinear crystals, beyond just being very much less expensive. For instance, it can be made in long lengths with low losses, it can be stretched and compressed and because the SON is induced, rather than being an intrinsic property, it can be tailored. These differences have recently proven to be significant for applications of poled fibre in SHG and sensing with very exciting results.

2. SON & Poling

Whilst much of the investigation of poling has been performed on small samples of bulk glass, the majority of applications research has utilized a special fibre. This Twin Hole Fibre (THF) has two small holes that run close and parallel to the core. Areas on the side of the fibre are carefully polished so as to break through into the holes and then electrodes are inserted (Fig 1). Typical poling conditions involve heating the fibre to 250-300 C and applying a field of 100 V/μm. This can induce an SON of ~0.5 pm/V.

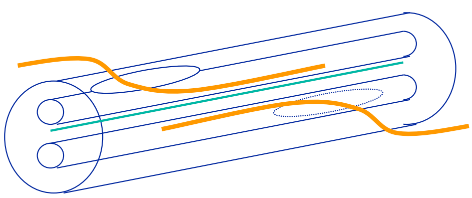

Fig. 1. Typical Poled Fibre Device

Whilst the details of the mechanism are complicated, there is strong evidence that it involves charge migration and trapping. The heat makes certain charged species mobile. They migrate under the influence of the applied field.

The heat is removed whilst the field is still applied and the charges get frozen in. This results in an internal space charge field E_{fif}, which acts on the Third Order Nonlinearity (TON) to produce a SON: $\chi^{(2)}_{ind} = 3\chi^{(3)} \times E_{fif}$.

If the internal field cannot exceed the breakdown strength of silica and the TON is fixed, there is clearly a limit to the achievable SON, and experimental results approach this theoretical limit. Whilst there are some indications that nano-crystallisation may allow higher TON, practically we currently limited to SON ~0.5 pm/V.

3. Fiber Optic Voltage Sensing

For many potential applications the currently achievable levels of $\chi^{(2)}$ are insufficient and cannot be compensated practically by making the devices longer. However this is not a significant concern is voltage sensing for electrical power applications. Such a sensor needs to measure the voltage of an electricity transmission line by determining the line integral of the electric field between the ground and the high voltage conductor. This involves large voltages and long lengths and hence can utilize the modest levels of $\chi^{(2)}$.

Such a system has been demonstrated [3] using a poled fibre with LEO of ~ 0.16 pm/V which is helically wound since the longitudinal EO component is zero. The birefringence of the LEO is utilized in the system and this is measured with a low coherence interferometer. [4] Whilst for a bulk uniaxial crystal this difference in electro-optic response between the two polarisation modes would be expected to be 3:1, in almost all twin hole fiber the response is much smaller, typically 1.15:1. [5] The poled fiber was coiled around a 95 mm diameter, 500 mm long, cylindrical former. To maintain the orientation of the fiber, which is critical, a special design of fiber with two flats is used. This sensor was placed inside a high voltage test enclosure (~22 kV RMS at 50 Hz). The response is shown in Figure 3 for averages over ten cycles and four seconds. The linearity between 2.5 kV and 12 kV RMS, where breakdown occurred, is good, particularly for the 4 s averaged values. The performance is close to that needed for energy metering applications. This demonstrates the feasibility of this voltage sensor and there is room for improvement especially in the LEO value which was small and in the birefringence of the LEO which in principle could be substantially increased.

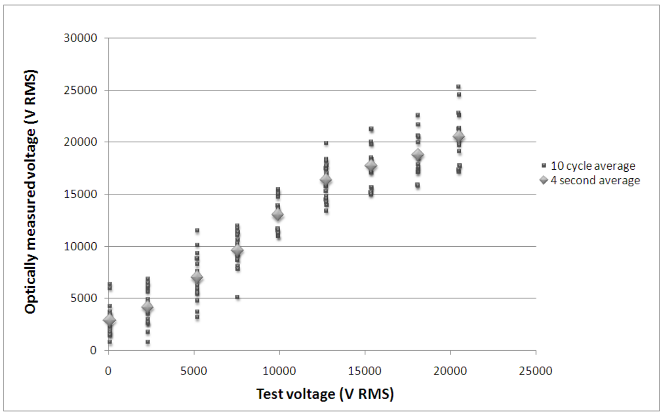

Fig. 2. Performance of Poled Fibre Voltage Sensor

4. Second Harmonic Generation

Whilst it has been clear for a long time that poled fiber has significant potential for SHG, there has been little research on this until recently. Most practical SHG devices rely on Quasi Phase Matching (QPM) to correct the walk off between the fundamental and the second harmonic. QPM is achieved through periodic variation of the poling.

Whilst crystalline devices are routinely periodically poled, poled fiber lends itself to this processing. The fiber may be directly periodically poled with either a suitable electrode geometry or with a scanning UV or CO_2 laser and control of the voltage during scanning. This approach lends itself to periodic poling where the direction of the non-linearity alternates periodically. The approach that has generally been taken is however that of uniform poling followed by periodic erasure, typically with a UV laser. This produces a structure that cannot be realized with crystals where there are alternate regions of zero and non-zero SON, although the main consequence of this structure is that the efficiency is 50% of the normal domain revered structure.

The substantially lower SON of poled fiber than crystals is readily mitigated by the fact that poled fiber devices can be significantly longer than crystal devices, albeit this comes with a bandwidth penalty. The other significant benefit of the fiber format is tenability through stretching or compression.

Recently there have been some impressive results demonstrating such devices. This includes 45 nm tunability using compression of the fiber [6] and conversion efficiencies for non-tunable fiber systems in the 5-10% range, with predictions of 50%. [7] The versatility of optical fiber, combined with the huge improvements in fiber lasers in recent years, creates significant scope for further development of these devices.

It should also be noted that such periodically poled fibers can be used to generate frequencies other than the second harmonic. Entangled quantum photon pair generation offers important scientific and technological possibilities and has been demonstrated using periodically poled fiber with pump power as low as 43 mw. [8]

5. Conclusion

Research on poling research has steadily revealed a large body of information on the mechanisms involved; of charge migration and trapping and the effects of interfaces. However, despite some intriguing results suggesting potential for large SON through inducing nano-crystallisation, .it seems unlikely that values exceeding 0.5 pm/V will be readily achievable in silica. For electro-optic switching this is a problem since either high voltages or long lengths would be required and both represent barriers to high speed operation.

The power industry needs to measure very high voltages and would ideally do so by performing a line integral of field from an overhead power line to ground. Poled fiber clearly lends itself to this application and compelling results have been demonstrated.

Periodically poled devices are used for frequency doubling lasers to provide new wavelengths. The very limited scope for tuning crystals constrains such QPMSHG devices to narrow wavelength bands. However periodic structures in optical fiber are readily compression tuned. When combined with the rapid advances in fiber lasers delivering huge power reducing the need for large nonlinearity, periodically poled fiber devices have demonstrated very impressive results in tunable frequency doubling.

Even without increases in the SON magnitude the prospects for applications of poled fiber technology in these areas are very promising.

6. References

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