Probing the anisotropy of optical fibres by Third Harmonic Generation

An optical fibre is a fantastic tool for confining light over a huge distance, especially in modern telecommunications. We now have available a broad range of optical fibres for diverse uses. For most applications, any effect that modifies the polarization of the light propagating in the fibre must be avoided. How can we accurately characterize these parasitic polarization effects, which are linked to unwanted birefringence in the fibre? It can be done using a protocol of nonlinear crystal optics, specifically Third Harmonic Generation experiments.

Third Harmonic Generation (THG) is a nonlinear interaction based on the third-order electric susceptibility of matter. It can exist in any medium, *i.e.* gas, liquids, glasses, crystals, without any restriction of symmetry. From the quantum point of view, it corresponds to the collapse of three photons into one, as shown in Fig. 1. So if $h\nu$ is the quantum of energy of each incident photon, where ν is the frequency of the associated wave, then the quantum of energy of the photons produced by third harmonic generation will be $3h\nu$, the corresponding wave being the third harmonic of the incident wave, which is then called the fundamental wave.

An optical fibre is a dielectric waveguide that confines the electromagnetic field in a cylindrical geometry. For the light to propagate, the fibre takes advantage of the physical phenomenon of total internal reflection, as shown in Fig. 2. In a collaboration with the cable company DRAKA, we have studied a 642-mm-long fibre of their design. This optical waveguide is made of two concentric cylinders of isotropic glasses (Fig. 2): The inner one is the core, made of silica (amorphous SiO_2) doped with a molar concentration of 37% of Germanium dioxide (GeO_2) of radius a = 2.19 µm, and the outer one is the "cladding", of larger radius and made of undoped silica. The light is confined in the core since its refractive index is much higher than that of the cladding.

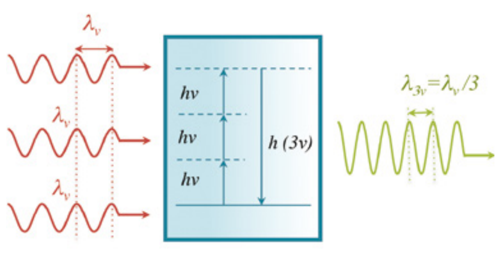

***Fig. 1**: Photonic diagram of third harmonic generation where λ_ν (= c/ν with ν the frequency) is the fundamental wavelength, $\lambda_{3\nu}$ is the third harmonic wavelength, and h is the Planck constant.*

This fibre should be fully isotropic. That is, the refractive index should keep a fixed value whatever the direction of polarization of the light. By studying third harmonic generation in this fibre, we have demonstrated that in fact it exhibits a significant anisotropy of the refractive index as well as of the third order electric-susceptibility tensor.

Contrary to the case of crystals exhibiting birefringence, *i.e.* crystals having, for a given direction of propagation, two possible values of the refractive index according to the polarization of the light, the only way to perform third harmonic generation efficiently in an optical fibre is to exploit two different modes of propagation for the two waves at ν and 3ν. These two modes will necessarily exhibit different geometries, but there may exist a frequency ν for which the effective refractive indices of the fundamental and third harmonic waves are equal, leading to momentum conservation and thus to a maximization of the THG efficiency. In the case of the fibre we used, this situation can be achieved when the fundamental wave is in the linearly polarized (LP) mode called LP01 at an expected value of λ_ν = 1550 nm, and the third harmonic wave, *i.e.* at $\lambda_{3\nu} = \lambda_\nu/3$, is in the LP03 mode, as shown in Fig. 2.

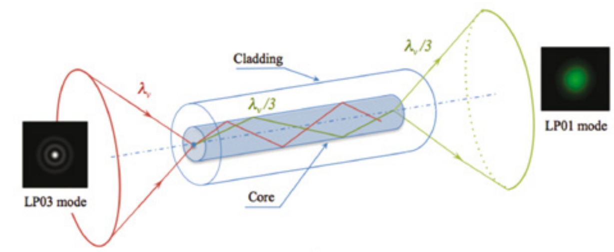

***Fig. 2**: Third Harmonic Generation performed in a step-index optical fibre. The two images show the transverse intensity profiles of the fundamental wave in the fibre's LP01 mode and of the third harmonic wave in the LP03 mode.*

We measured the spectrum of this third harmonic wave for different orientations of the linearly polarized fundamental wave. We found that the wavelength where third harmonic generation is observed, *i.e.* $\lambda_{3\nu}$, varies between two extreme values, *i.e.* 516.4 nm and 516.9 nm, corresponding to two particular perpendicular directions of polarisation. This difference of wavelength indicates that the refractive index of the fibre is anisotropic, and it can be used to estimate the birefringence, which we found to be equal to 9×10^{-5}.

From measurements of the intensity of the third harmonic wave as a function of the polarization angle of the fundamental wave, we observed a complex polarization behaviour. Since this fibre is not coiled, that is to say it is without any extrinsic mechanical stress, we explain the results by stating that the fibre exhibits an intrinsic uniaxial strain due to the material itself. We performed calculations by taking into account the non-linearity under strain and all the possible configurations of polarization for the fundamental and third harmonic waves and we found a remarkable agreement between measurements and calculations.

Thus, we have demonstrated that Third Harmonic Generation provides an excellent tool for analyzing the weak intrinsic anisotropy of an optical fibre. Also, this work should allow us to best design a method, using fibres, for the generation of "triple photons", a new state of light produced by third order spontaneous parametric down-conversion, which is the exact reverse process of third harmonic generation.

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FURTHER READING...

"Multiple intermodal phase-matched third-harmonic generations in a silica optical fiber"
A. Borne, T. Katsura, C. Félix, B. Doppagne, P. Segonds, K. Bencheikh, J.A. Levenson and B. Boulanger
***Optics Communications* 358**, 160 (2016).

"Anisotropy analysis of third-harmonic generation in a germanium-doped silica optical fiber"
A. Borne, *et al.*
***Optics Letters* 40**, 982 (2015).