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Invited talk at:
Second French Israeli Symposium on Nonlinear Optics
May 25-29, 1992, Port Barcarès, France

Nonlinear Optics in Fibres: A History of Overturned Assumptions and New Physics?

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Abstract

Fibre optics has repeatedly challenged our assumptions and surprised us with novel nonlinear phenomena and unexpected physical effects. Some striking recent examples, including optically-induced changes in material properties, are discussed.

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When optical fibres first appeared on the scene in the late sixties and early seventies, the aim was to prove that they offer a low-loss, dispersion-free means of transmitting optical signals over long distances. Losses of a few dB/km, rapidly obtained in silica glass fibre with GeO_2 as core dopant, seemed almost too good to be true. The further discovery of two windows of extra-low transmission at 1.3 and 1.5 μm, and a point of zero group velocity dispersion at 1.3 μm, had a great impact on further developments. Since then, losses in a typical high-quality fibre have dropped still further, to a small fraction of a dB/km at 1.5 μm, and repeater distances of 30 km are not just talked about but are being implemented in trans-oceanic links.

This background makes all the more extraordinary the blossoming of nonlinear optics in fibres. Many significant and often anomalous optical nonlinearities appear – against all initial expectations – in the core glass. The reasons for this are twofold: 1) very long usable optical path lengths (exceeding by several orders of magnitude those in bulk nonlinear optical experiments) and 2) tight lateral confinement of the optical power. These combine to allow normally tiny nonlinear perturbations to accumulate, building up into quite substantial signals.

An important attribute of a perfect transmission system is the absence of degradation with time. Photosensitivity, in the form of colour-centre formation or optically-induced changes in refractive index, birefringence or nonlinearities, is undesirable and indeed is not a problem at low powers in the infra-red spectral region; however, even at modest blue, green and ultra-violet intensity levels (a few mW per μm^2), germanosilicate glass (the common core material) turns out to be highly photosensitive[1,11]. During the last six years or so this has lead to a range of new in-core linear and nonlinear grating devices, which could not otherwise be realised except by complicated etching processes.

Thus, the presumption of a conveniently "dead" fibre core material has proved misplaced. Index changes as high as a few parts in 10^{-3} (extending out to the infra-red) have been induced in germanosilicate fibre; and a further fascinating effect, currently being explored at the ORC, shows induced birefringence as high as 10^{-5}, lining up with the linearly polarised field of the exposing radiation. Unique holographically-written polarisation filters and converters become possible, and a range of highly sophisticated grating devices realisable[7,12]. An area of great interest is the real-time interaction between the changes in index and birefringence and the optical fields that give rise to them. Experimentally it has been shown that the induced birefringence is reconfigurable, i.e., it can be erased and re-written with a different orientation as often as desired. This results in very strong, very slow nonlinearities that respond (unlike the optical Kerr effect) to the field average over a large number of optical cycles.

The goal of efficient second-harmonic generation in optical fibres is very desirable. A few years ago one would probably have been mocked for suggesting that an amorphous material could be prepared optically in such a way as to yield quite respectable efficiencies of conversion per mW. This view, too, has had to be abandoned in the face of experimental evidence to the contrary. It turns out that a novel form of nonlinear holography, involving the mixing of pump and second harmonic light, gives rise to a periodically reversing dc polarisation which – it is thought via quantum interference effects – causes the build up of an internal dc field which breaks the centrosymmetry of the glass and permits an electric-field induced second order nonlinearity to appear[2]. Early work at Southampton[11] showed that excitation poling via built-in capillary electrodes in the presence of blue or ultra-violet light gave $\chi^{(2)}$'s some 0.01× that of $LiNbO_3$. Recent work in New Mexico[8] reports that thermal poling (250°C) of commercial silica glass results in induced $\chi^{(2)}$'s of the order of a third the commonly-used value in $LiNbO_3$, in a surface layer next to the poling anode. The stage seems set, therefore, for dramatic developments in parametric frequency conversion in optical fibres, using thermally-driven periodic poling to achieve quasi-phase-matching.

Optical switching, which relies on a third order non-linearity, is clearly permitted in glasses. In many devices, such as the Sagnac loop and directional coupler, it is caused by a nonlinear phase shift $\Delta\phi$ between two guided modes; if $\Delta\phi = \pi/2$, the output state changes from 0 to 1. In practice, this picture only works well if the momentum difference between the modes is much greater the nonlinear momentum, for otherwise the eigenmodes of the waveguiding structure are severely perturbed by the nonlinearity, rendering the switching process more complex. Thus, multiple and single coupling length devices switch in different ways. Useful orders of merit can be defined by relating the single and multi-photon absorption parameters to the nonlinear index parameter. Clearly, if the characteristic length associated with a multi-photon absorption exceeds the length needed for a $\pi/2$ nonlinear phase shift, nonlinear switching will be inefficient.

A fascinating new area, subject of recent theoretical study, is that of nonlinear propagation in periodic media[5,13]. The ability to write highly perfect distributed feed-back gratings into single mode fibre cores opens the prospect of modulational instability gain and soliton formation in fibres. Approaching the stop-band edge from the blue (red) side of the Bragg condition, the group velocity dispersion tends to negative (positive) infinity. This permits cancellation of positive or negative material GVD, avoiding the need to work near the 1.3 μm zero order dispersion point if soliton formation is sought. It may be shown that oscillation, short pulse formation and soliton pulses with very small group velocities are feasible in this regime. A recently developed Bloch wave approach has lead to analytical expressions for the modulational instability gain[13].

Stimulated Brillouin scattering (SBS) was rapidly identified to be of crucial importance in fibre communications systems when the linewidth is narrow and the optical path lengths large. Recently, a new kind of SBS in fibre has been discovered[14]. It involves the parametric interaction of acoustic flexural phonons with photons in the LP_{01} and LP_{11} modes of a fibre, produces a stimulated Brillouin signal (shifted some 20 MHz at 500 nm) in the forward direction, and has a gain that depends – most anomalously – on $(r_{eq}/a)^4$, where r_{eq} and a are the mode and fibre radii. This has to do with the acousto-optical overlap and the fact that it is an electrostrictive moment (not a pressure) that determines the acoustic gain. FSBS is an unusual phenomenon for a number of reasons, including: a) challenging the common presumption that all nonlinear effects become more important as the optical intensity rises; and b) offering a type of intermodal Bragg scattering that is almost independent of the wavelength (this arises because the intermodal beat period is approximately constant over ≈ 0.05 of the optical baseband frequency in the dual-mode range).

Finally, the arrival of the Erbium-doped fibre amplifier (EDFA) represents the dawn of a new era in optical fibre research[4]. Already the femto-second fibre soliton laser, making use of both optical nonlinearities and the EDFA, is creating a stir[6,10]. The EDFA is likely to have a significant impact in other areas of nonlinear fibre optics, such as nonlinear switching[15], Brillouin[9] and Raman scattering, where the presence of optical gain (instead of the usual loss) challenges all the standard assumptions and approximations. Nonlinear fibre optics seems set to continue to overturn our assumptions and surprise us with new physics.

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