SOLITARY THERMAL SHOCK-WAVES AND OPTICAL DAMAGE IN OPTICAL FIBRES

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Thermally-induced catastrophic optical breakdown is clearly of great importance for fiber-based laser-light delivery systems. Fiber core can be destroyed irreparably at rates of 1 m/s by breakdown that starts at a locally heated point and travels back towards the laser; that the damage tracks left behind are often elegantly uniform and periodic is only a slight recompense. Breakdown can occur at relatively modest intensities (we have recorded 2.8 mW/μm^2 in a multimode fibre at blue/green wavelengths), and has been observed in many different fibres at both Ar^+ and Nd:Yag laser wavelengths[1-4]. We initiate the effect by heating the fibre with a small flame whilst the laser light is propagating within it. A solitary thermal shock-wave is created which propagates along the fibre towards the laser, leaving the core permanently damaged and unable to guide light. Associated with this shock-wave is a bright spot of side-scattered light which can be observed propagating along the fibre; for this reason we have named the effect the "fibre-fuse". Similar thermal shock-waves have previously been seen in gases ("laser-induced deflagration waves")[5].

These shock-waves are initiated by thermally-induced absorption within the fibre. When the fibre is heated above 1000°C, a sharp rise in absorption is seen, as shown in Fig.1. This increase can be attributed to the creation of defect centres in the glass matrix and can be modelled quite accurately using an Arrhenius equation:

$$\alpha(T) = \alpha_0 \exp\{-E_f/k_b T\}, \qquad T<T_m$$

where E_f is an energy of formation, k_b Boltzmann's constant and α_0 a constant. This rise in absorption leads to a further temperature increase in the core, which in turn raises the absorption to a still higher level, leading to thermal run-away. This continues until the core glass melts. We have observed that after melting, the core glass becomes super-absorbant; it is this sudden rise in absorption that leads to the formation of a stable solitary thermal shock-wave, thermal dissipation (causing pulse spreading) being balanced by laser heating (causing pulse peaking).

We have successfully modelled this effect both numerically and analytically. In the first case we adopted a finite element approach in which the fibre was divided up into a number of constant temperature nodes. Starting with an arbitrary initial temperature profile it was then possible to model the evolution of the temperature by tracking the unsteady heat flow between these nodes, as well as the heat absorbed by them from the laser light. Heat loss to the coating is neglected; this is a reasonable approximately if the cladding temperature does not rise much above the ambient temperature T_a. The evolution of a stable travelling thermal shock wave is shown in Figure 2, starting with an initial arbitrary Gaussian temperature profile at a peak temperature of

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3000°C; for fuse initiation this temperature must exceed a threshold.

In order to model the effect analytically, the fibre cross-section was divided into two "lumped" temperature regions comprising the core and cladding. Heat loss to the coating was again neglected. Non-linear differential equations were developed for the core and cladding temperatures. There is not room here, however, to describe these equations in detail; they will be presented elsewhere[6]. These equations give temperature profiles which agree closely to those obtained by finite element analysis,and also enable us to look at the relationship between fuse velocity and intensity for stable solitary thermal shock-waves.

The nature of the residual core damage seen in the fibres is intriguing; a periodic pattern is seen from the side when the damaged fibre is observed under a microscope and in some fibres this can be uniform over tens of centimetres. This periodicity may be accounted for through instabilities in the mode diameter d of the guided light. High temperatures in the leading edge of the shock-wave induce refractive index changes (for silica $\partial n/\partial T = 1.23\times10^{-5}$ at 550nm), leading to the formation of a thermal lens in the vicinity of the shock-wave. This lens will focus the light down to a smaller spot-size d; since the shock-wave velocity v_f and peak temperature T_p are sensitive to small changes in d, and the focal length of the thermal lens itself depends on v_f and T_p, instabilities in v_f and T_p seem likely to result, leading to focusing and defocusing of the light in the core. Higher temperatures will be attained in the regions of tighter focusing, thereby leading to permanent damage. This scenario will be explored in more detail in a subsequent publication.

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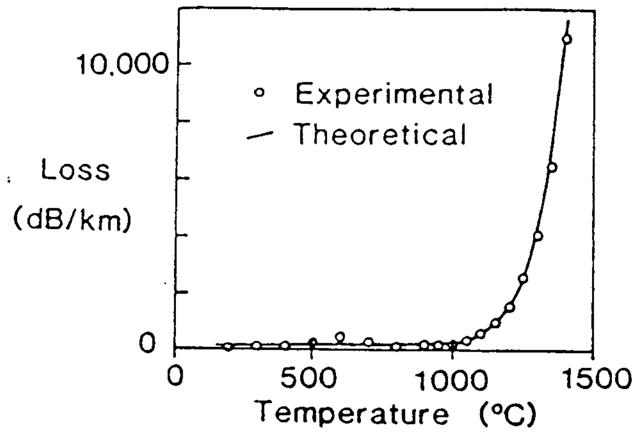

Figure 1 Temperature dependence of attenuation in a Ge-doped multimode fibre measured at 500nm.

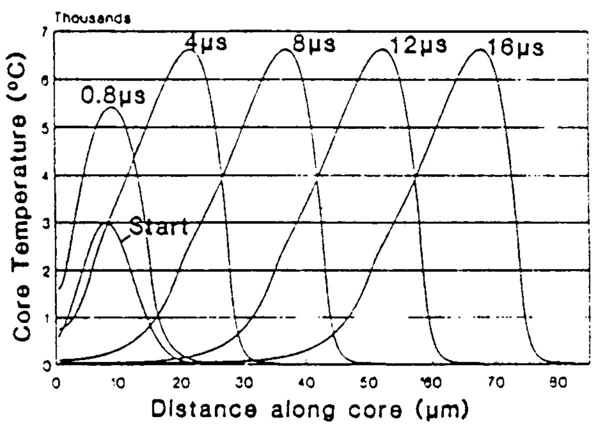

Figure 2 Evolution of stable travelling thermal shock wave from an initial Gaussian peak (3000°C, HWHM 5μm) using modal analysis.