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Soliton-like thermal shock-waves in optical fibres: Origin of periodic damage tracks

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Abstract

The periodic damage track left after the passage of a soliton-like thermal shock-wave along an optical fibre is shown to arise through mode focusing in the thermal lens created by the shock-wave.

Introduction

Catastrophic optical breakdown in single and multi-mode germanosilicate optical fibres, leading to the formation of soliton-like thermal shock-waves (SLTSW's), has been the subject of several recent papers[1-3]. We have shown[1] that the effect is initiated by generation of large numbers of loss-inducing defects at temperatures above about 1000°C. If the ambient temperature of a fibre carrying sufficient power (more than about 10 mW/μm^2 Ar^+ all lines in germanosilicate fibres) is raised by external heating (for example with a match flame), thermal runaway leads to the melting and even vaporisation of the core. The melted/vaporised core has extremely high loss (all the incident light can be absorbed in perhaps 10 μm), and this fuels the stable existence of a superheated spot or SLTSW that travels towards the laser at a constant velocity, damaging the fibre as it goes. By developing and solving a pair of non-linear differential equations for the core and cladding temperatures, we have been able to confirm many of the main experimental characteristics of the phenomenon. An intriguing additional feature of the effect is the appearance of highly regular periodic damage tracks (see Figure 1) whose periodicities scale with the mode-

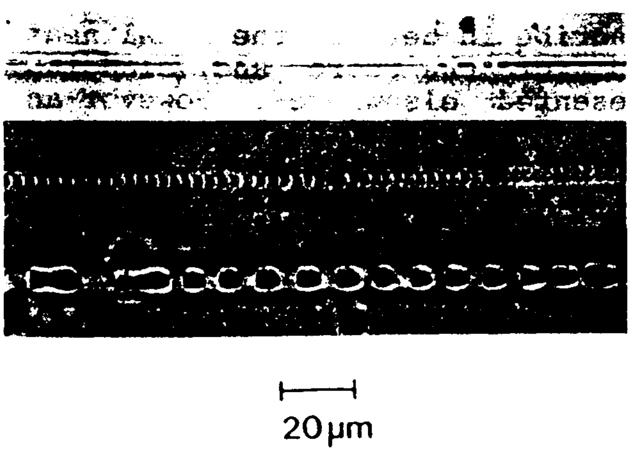


Figure 1. Some examples of the damage tracks created by the passage of SLTSW's.

spot diameter. Here we will show that these tracks are the result of instabilities in SLTSW temperature and velocity caused by focusing and defocusing in the thermal lens created <u>in front</u> of the hot-spot, i.e., <u>before</u> the fibre core has melted/vaporised.

The mathematical model

The loss in the fibre as a function of temperature is an important prerequisite for modelling the effect. Experimental measurements of the short-term loss induced at different temperatures in a germanosilicate fibre follow the following Arrhenius equation below the melting point ($T=T_m$ K):

$$\alpha(T) \quad = \quad \alpha_0 \exp\{-E_f/k_B T\}, \qquad T<T_m \tag{1}$$

where E_f is the energy of formation of loss-inducing defects, k_B is Boltzmann's constant and α_0 a constant. ESR studies of damaged fibre confirm the formation of defects, showing a strong Ge E′ fingerprint. Equation (1) fits our experimental data to an accuracy of ±4% with E_f = 2.2 eV and $\alpha_0 = 1.2\times10^6$ m^{-1} per mol% GeO_2 at 500nm. Above T_m, the loss rises abruptly to a much higher level, so that for modelling a propagating SLTSW (as distinct from the initiation thereof), the following simple expression may be used:

$$\alpha(T) \quad = \quad 0 \text{ for } T<T_m, \text{ and } \alpha_p \text{ for } T>T_m \tag{2}$$

The accuracy of this expression is illustrated in Figure 2.

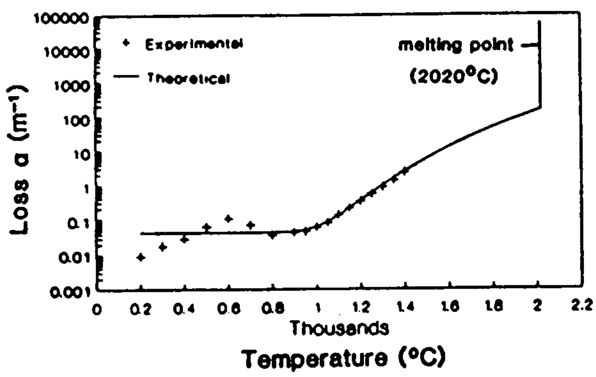


Figure 2 Short-term loss induced by heating fibre in tube furnace (experimental points) with theoretical fit to Arrhenius equation. $\alpha_p = 5.6\times10^4$ m^{-1} is the loss in the molten/vaporised core[2].

There is not room here to describe in detail the non-linear equations we have developed for the core and cladding temperatures; they will be presented elsewhere[2]. However an instructive 1-dimensional solution arises if heat loss to the cladding is neglected - a fair approximation if the ratio of core area to volume is small. The relationship between velocity v_f and average in-spot intensity I_0 (calculated for spot-size diameter d) for a single SLTSW turns out as follows:

$$\left(2\rho v_f C_p/k\alpha_p\right) \quad = \quad -1 \quad + \quad \left(1 + \{4I_0/k\alpha_p(T_m-T_a)\}\right)^{1/2} \tag{3}$$

where T_a is the ambient temperature, C_p the specific heat, ρ the density and k the thermal conductivity. The corresponding SLTSW temperature profile takes the form:

$$T = T_a + \left[I_0\alpha_p/k\gamma(\alpha_p+\gamma)\right]\exp\{-\gamma\eta\}, \qquad 0<\eta$$

$$T = T_a + \{I_0/k\gamma\}\left[1 - (\gamma/\alpha_p+\gamma)\exp\{\alpha_p\eta\}\right] \qquad \eta<0 \qquad (4)$$

where γ is defined by $\gamma=\{\rho v_f C_p/k\}$, $\eta=(z-v_f t)$ is the propagation parameter, z the axial coordinate and t the time. Note that $\eta = 0$ is specified as the point where the loss first becomes non-negligible; in our approximate representation of the loss this occurs at $T=T_m$ when the loss jumps abruptly to α_p. The ultimate temperature reached by the core is $T_p = T_a+\{I_0/\rho v_f C_p\}$, which agrees with the results of a simple thermal balance.

The periodic damage tracks

The periodic damage tracks may be accounted for through instabilities in the mode diameter d of the guided light. The high temperatures in the leading edge $\eta>0$ of the SLTSW induce refractive index changes (for silica $\partial n/\partial T = +1.23\times10^{-5}$ at 550nm). The parameter γ yields the rate of temperature fall-off in this region, and so allows us to establish the dimensions of the ellipsoidal thermal lens that forms in front of the SLTSW before the glass melts. The aspect ratio of the lens ellipse is given approximately by the product $\gamma d/2$. The effect of the lens is to cause the incident mode to focus down to a spot size smaller than that in a cool fibre. Since v_f and T_p are sensitive to small changes in d, instabilities in the soliton velocity and temperature result. The half-length $L_d = 1/\gamma$ of the temperature decay is plotted in Figure 3 against the spot diameter d at a constant power of 100 mW. T_p and v_f are also plotted; notice the dramatic increase in temperature as d is reduced. The corresponding temperature profiles are plotted in Figure 4. Although this 1-dimensional

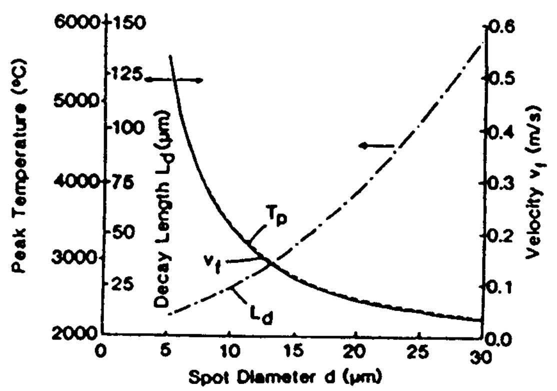


Figure 3 Plots of v_f, T_p and L_d against mode spot-diameter d at a constant power of 100 mW. The other parameters used were: T_m=2020°C, C_p=788 J/kgK, ρ=2200 kg/m^3 and k=9.2 W/mK.

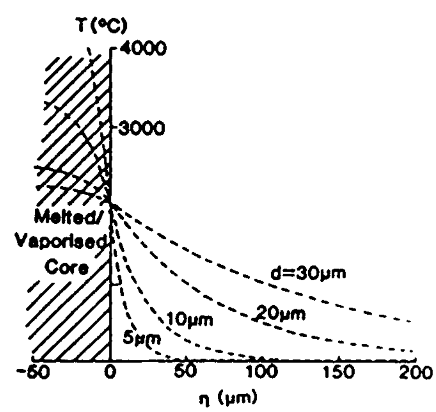
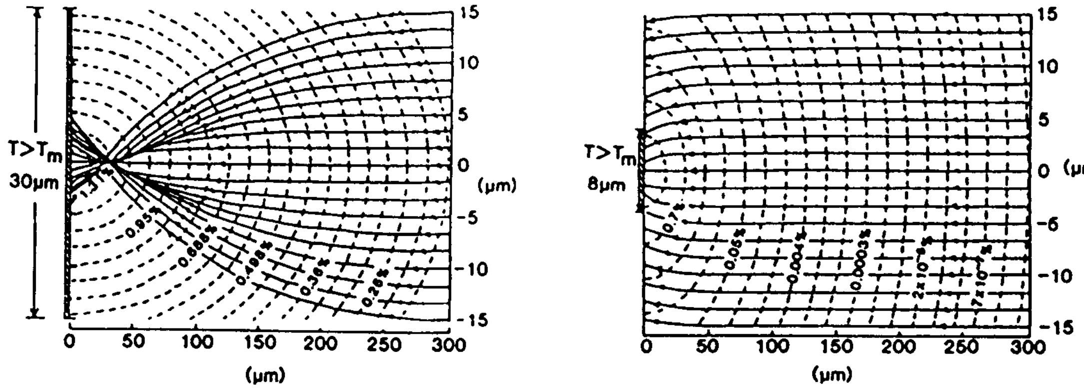


Figure 4 The temperature profiles of SLTSW's at a power of 100 mW and various different mode spot diameters.

model ceases to be very accurate for small spot sizes, when heat loss to the cladding is significant, the temperature trend is correct. Ray traces of the spot focusing in two cases are shown in Figure 5. Starting with a spot size of



(i) (ii)

Figure 5 Ray traces of the focusing of 100 mW of guided light in two cases: i) with a 30 μm wide SLTSW, and ii) with an 8 μm wide SLTSW. $\partial n/\partial T = +1.23\times10^{-5}$ is assumed. It can be seen that both SLTSW's are unstable since the nominal spot-sizes are not maintained; it is likely that oscillation will occur between these two extremes.

d=30 μm in a multimode fibre, the thermal lens that results will focus the light down to a mere 8 μm; recalculating the thermal lens for the 8 μm spot yields very little focusing, and the spot size reverts to 30 μm. It is probable that oscillation between these two extremes will result as the SLTSW propagates along the fibre at velocities that swing up and down over the range $0.03<v_f<0.25$ m/s. For the 30 μm spot-size, T_p is about 2200^{o}C, and the core will merely melt, leaving no permanent damage; however for a 8 μm spot T_p soars to 4000^{o}C, causing core vaporisation and permanent chemical breakdown of the glass.

Conclusions

The periodic damage track characteristic of the passage of a soliton-like thermal shock-wave (SLTSW) is caused by lateral instabilities in the mode spot size. Calculated SLTSW temperature profiles based on a constant spot-size are inherently unstable because the thermal lens they create causes inevitable focusing and thus alters the spot-size and the SLTSW velocity and peak temperature.

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