Solitary thermal shock waves and optical damage in optical fibers: the fiber fuse

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Fresh experimental and theoretical results on thermally induced catastrophic breakdown (the fiber fuse) in optical fibers are presented, including the observation that the damage is not always irreversible and an analysis of the complex unsteady absorption–heat-conduction process that controls the effect. Good agreement with experiment is obtained with just two independent parameters. The analysis shows that the fiber fuse is a new kind of solitary thermal shock wave in whose leading edge the temperature gradients can reach several thousand kelvins per micrometer.

Thermally induced catastrophic breakdown in optical fibers carrying modest average power densities is a phenomenon that has only recently become the subject of detailed investigation, although informal reports of the effect date back some years.[1] As many of its basic experimental features have already been reported,[2–4] we concentrate on new findings.

We have been able to initiate the fiber fuse, so named[4] for its striking resemblance to a fuse, in a wide range of fibers at in-core intensities (all visible lines of Ar^+ laser light) sometimes as low as 2.8 mW/μm^2 (in a multimode fiber, numerical aperture 0.21, core diameter 40 μm). Our experimental technique involved heating a stripped section of fiber with a match flame. The residual core damage left behind after passage of the fuse often consisted of regular repetitive sequences of bullet-shaped zones[2–4] (pointing away from the light), with single, double, and even triple periodicities. In each case the periods were slightly larger than the mode diameter. In few-moded fibers the damage occasionally took the form of long nonperiodic filaments. We cleaved through a number of the dark-colored bullet zones and examined both etched (in HF) and unetched cleaves in a scanning electron microscope. Before etching, the bullet zones were composed of solid material; they etched much faster than the surrounding undamaged cladding, leaving a deep etch pit. Undamaged fiber did not exhibit preferential etching. Microprobe Raman studies[3] indicate that free oxygen is liberated in the bullet zones; we suspect therefore that they may be porous.

It is well known that conventional self-focusing can create periodic damage tracks in bulk glass[5,6]; however, a number of features distinguish the fiber fuse from this phenomenon. The velocities are some 10^6 times slower, the power is orders of magnitude smaller than the critical power for self-focusing in silica (~90 kW), and, furthermore, the fuse does not start spontaneously. We believe that the damage tracks are caused by thermal lensing (see the concluding paragraph).

Using a calibrated integrating sphere, we were able to establish that about 95% of the power in the incident laser light goes toward heating the fiber. The remaining 5% is reradiated. Using an Anritsu spectrum analyzer in the range 600–1300 nm, we were able to measure the spectrum of light backscattered from the propagating fuse in a fiber with a 40-μm spot size at an intensity of 2.8 mW/μm^2 (Fig. 1). This spectrum deviated significantly from blackbody behavior (a rough fit yields a temperature of ~5400 K), suggesting, together with the fact that the conductivity of silica rises with temperature, that the hot spot at the fuse center is plasmalike.

We investigated fuse initiation by heating a range of different fibers with varying Ge concentrations in a tube furnace and measuring the absorption at successively higher temperatures. Only the short-term effect (which reaches a fairly steady state after a few seconds at each new temperature) is of significance for fuse initiation; it rose rapidly with temperature above 1000°C (Refs. 2 and 3) and scaled roughly linearly with the Ge concentration. This behavior may thus be linked to the creation of Ge-related defects and up to the melting point ($T = T_m$) is modeled quite accurately using an Arrhenius equation:

$$\alpha(T) = \alpha_0 \exp(-E_f/k_B T), \qquad (1)$$

where k_B is Boltzmann's constant. This expression fits our experimental data to ±4% over the range 20–

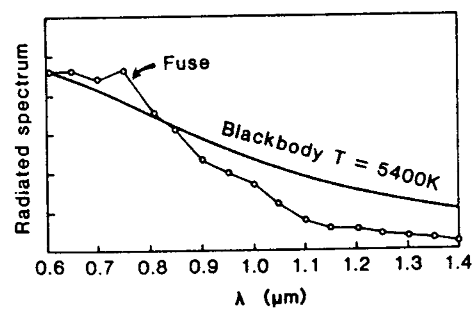

Fig. 1. Spectrum of backscattered radiation from the fuse at $d = 40\ \mu$m, $d_0 = 125\ \mu$m, $I_0 = 2.8$ mW/μm^2, $v_f = 0.16$ m/sec. The solid line is the blackbody radiation curve for 5400°C.

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1600°C at $E_f = 2.2$ eV and $\alpha_0 = 1.2 \times 10^6$ m^{-1} per mol % GeO_2 at 500 nm. Electron spin resonance studies of damaged fiber show a strong Ge E' fingerprint, providing further evidence that Ge-related defects play a role in the phenomenon.

We have tested Eq. (1) in the case where the core intensity is below the critical threshold for fuse propagation at an ambient temperature T_a of 293 K. When the fiber (GeO_2 dopant concentration 10 mol %) was heated with a flame ~5 mm wide, the loss in the heated section rose to ~0.2 mm^{-1}, corresponding from Eq. (1) to a core temperature of ~2300 K. A bright spot then appeared at the hottest part of the flame and propagated out of it against the light for several millimeters before disappearing again.

This experiment then yielded a most intriguing and unexpected result; this sequence of events *repeated* itself at intervals of ~1 sec over the same section of fiber. During each cycle the absorption in the heated section rose to a high level while the hot spot was present, recovering to ~0.2 mm^{-1} after the spot disappeared. This reversible core breakdown was not reported before; it may have profound implications for the usefulness of the effect in laser welding and writing phase gratings into the core.

When the core intensity is above the critical threshold for fuse propagation, raising T_a increases the absorption and hence drives the core temperature T still higher, until $T > T_m$, when it melts and then (if the power is sufficient) vaporizes. It is presumed therefore that above some threshold temperature $T_t > T_m$, the absorption in the core rises abruptly to a high level, permitting the existence of a solitary thermal pulse that travels into the face of the light at a constant velocity. Thermal diffusion (causing pulse spreading) is balanced by the absorption of light (causing pulse peaking), and the result is a stable temperature profile at a fuse velocity v_f. The fiber fuse appears to be an interesting new solid-state instance of the laser-induced deflagration waves already known in gases.[7]

The critical threshold intensity for stable fuse propagation at constant T_a depends on enough optical power's being absorbed to offset loss of heat from the fuse center. Any model must therefore include both axial and radial heat diffusion; heat loss to the coating may be neglected provided the cladding temperature does not rise much above T_a. We have developed a quasi-two-dimensional approach to the problem in which the fiber is divided into two lumped temperature regions comprising the core and cladding. The analysis gives the parametric relationship between the fuse velocity and the core intensity with just two independent parameters—the temperature T_t at which the absorption abruptly becomes large and the absorption level α_p that is attained when $T > T_t$ in the superheated core. To facilitate the analysis that follows, we have assumed arbitrarily that α_p is constant. The search for self-consistent traveling-wave solutions of the unsteady heat-transfer equations, including absorbed optical power and thermal conduction but neglecting radiative heat transfer, leads to the following pair of nonlinear differential equations:

$$\Gamma S - (I_0/k)\left[1 - \exp \int_0^{\eta} \alpha(T)\mathrm{d}\eta\right] = 0,$$

$$\Gamma(\theta - T_a) + [16d/d_0(d_0^2 - d^2)] \int_0^{\eta} (T - \theta)\mathrm{d}\eta = 0. \quad (2)$$

The operator $\Gamma = [\mathrm{d}/\mathrm{d}\eta + (\rho v_f C_p/k)]$ and $S = (T - T_a) + (\theta - T_a)[(d_0/d)^2 - 1]$, where d and d_0 are the mode-spot and fiber diameters, T and θ are the core and cladding temperatures [at the zone center radii of $d/4$ and $(d_0 - d)/4$], C_p is the specific heat, ρ is the density, k is the thermal conductivity, and I_0 is the average intensity in the mode spot. The propagation parameter η is defined by $\eta = (z - v_f t)$, where z is the axial coordinate and t is the time. $\eta = 0$ specifies the point where the absorption first becomes nonnegligible; the hottest part of the fuse will always appear at $\eta < 0$. The quantity S is proportional to the total excess thermal energy per unit fiber length at any point along the pulse. It will grow steadily until the light intensity falls below the level needed to sustain a core temperature greater than T_t; at this point the absorption returns to a much lower level, and thereafter S remains more or less constant. If all the light is absorbed (as will happen if the fiber core gets irreversibly damaged), then S will attain the value $I_0/\rho v_f C_p$; in this case the ultimate temperature reached by the whole fiber sufficiently far behind the fuse (i.e., when $T = \theta$) is given by $T_a + (I_0 d^2/\rho v_f C_p d_0^2)$, which agrees with the results of a simple thermal balance.

Equations (2) are difficult to solve exactly, even using numerical methods; however, the absorption in Eq. (1) takes several seconds to develop, whereas the material on the leading shock-wave edge has only a few microseconds to respond. This means that it is accurate to assume (for a propagating fuse) that the absorption just below T_t is so much smaller than α_p that

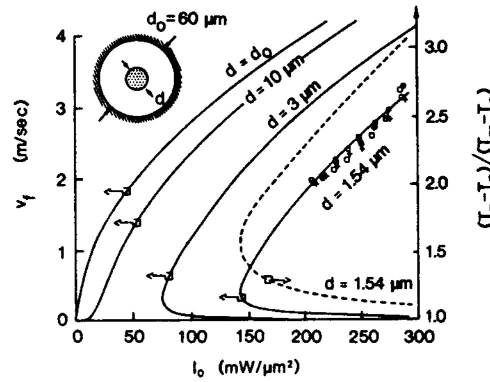

Fig. 2. Velocity versus intensity for a variety of different fiber geometries (inset is schematic diagram of fiber cross section, with d being the mode-spot diameter). Note that the curve for $d = d_0$ applies to the one-dimensional case when no heat is lost to the cladding. The experimental data points for $d = 1.54$ μm (fit achieved at $\alpha_p = 5.6 \times 10^4$ m^{-1}) agree well with the theory; the peak core temperature T_p, normalized with respect to T_m, is also plotted in this case. In a fiber with $d = 40$ μm and $d_0 = 125$ μm, $I_0 = 2.8$ mW/μm^2 was sufficient to sustain fuse propagation at $v_f = 0.16$ m/sec, close to the origin of this plot.

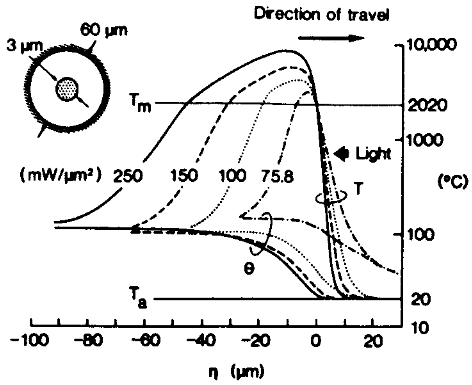

Fig. 3. Solitary-wave temperature profiles (T, core temperature; θ, cladding temperature) for a variety of different intensities at $d = 3$ μm and $d_0 = 60$ μm. Note that the absorption in the core has been assumed reversible; hence the change in slope in the trailing edges of the higher-intensity profiles.

it can be neglected. With use of this approximation, analytical solutions exist for Eqs. (2) in the hot spot ($T > T_t$, $\alpha = \alpha_p$) and in the leading and trailing edges of the pulse ($T < T_t$, $\alpha = 0$). Matching S, $dS/d\eta$, θ, and $d\theta/d\eta$ at the interfaces between these regions (i.e., the two points where $T = T_t$) yields, after some manipulation, a pair of complicated transcendental equations relating the fuse velocity to the value of η, where $T = T_t$ on the trailing edge of the thermal shock wave (on its leading edge this occurs at $\eta = 0$). Here we do not include the details of these equations; however, a non-transcendental equation arises in the one-dimensional case when heat loss to the cladding is neglected (i.e., $d = d_0$). Under these circumstances the relationship between v_f and I_0 is

$$(2\rho v_f C_p/k\alpha_p) = -1 + \{1 + [4I_0/k\alpha_p(T_t - T_a)]\}^{1/2}. \quad (3)$$

In this case, the fuse velocity scales as $\sqrt{I_0}$ at core intensities $I_0 \gg k\alpha_p(T_t - T_a)$. By exploiting the linear attenuation in small-cored fiber to obtain an axial variation in in-core intensity, we were able to measure v_f at several different values of I_0. The results of this measurement in a fiber with $d = 1.54$ μm and $d_0 = 60$ μm show good agreement (Fig. 2) with the full two-dimensional analysis for $C_p = 788$ J/kg K, $\rho = 2200$ kg/m^3, and $k = 9.2$ W/m K. The best fit occurred at $\alpha_p = 5.6 \times 10^4$ m^{-1} for $T_t = T_m = 2020$°C. This estimate of α_p reflects implicitly the effects of nonlinear absorption and latent heats of phase transition in the core. $T_t = T_m$ was chosen as a rough approximation; if T_t were much hotter than T_m it would be less likely that the fiber fuse could ever be reversible as observed. Other measurements on fibers with different geometries agreed with theory to ±10%. Figure 2 shows that a threshold intensity exists below which the fuse cannot be excited; this threshold is highest when the ratio of core surface area to volume is largest (the lack of a threshold for large spot sizes, i.e., $d \to d_0$, is an artifact of the assumption that no heat is lost to the coating). Above this threshold, two solutions exist at any given core intensity, one fast and the other slow. On the leading edge of the pulse the slow solution has a large amount of thermal energy in the cladding, whereas the fast solution has little. It can be shown that the slow waves are unstable, evolving rapidly into fast ones.

Temperature profiles for $d = 3$ μm and $d_0 = 60$ μm, obtained from the full quasi-two-dimensional analysis, are given in Fig. 3 for a range of different I_0 values. Since its peak core temperature just exceeds $T_t = 2020$°C, the profile for $I_0 = 75.8$ mW/μm^2 is close to cutoff; the conditions here are probably close to those obtained experimentally in the reversible fuse where, although the fuse did propagate, its peak temperature was not high enough to cause permanent damage. The core temperature on the leading edge of the shock wave grows approximately as $(T - T_a) = (T_t - T_a)\exp(-\eta\rho v_f C_p/k)$; this expression holds exactly for the one-dimensional case. Figure 2 yields $v_f = 3.5$ msec^{-1} at 250 mW/μm^2 for $d = 3$ μm, giving a temperature gradient at $\eta = 0$ of 1320 K μm^{-1}, which represents a severe thermal shock.

The periodic damage tracks may be accounted for through unstable thermal lensing. High temperature in the leading edge of the fuse induce a thermal lens ($\partial n/\partial T$ for silica is $+1.23 \times 10^{-5}$ at 550 nm), which causes the incident mode to focus down in the region $\eta > 0$, changing the effective spot size d at the fuse. Ray traces based on calculated temperature profiles confirm this conjecture. Since v_f and T_p are highly sensitive to small changes in d (calculations show that a reduction in d from 3 to 1.5 μm at a constant power of 700 mW causes a fourfold increase in v_f and a rise in T_p of 3500°C) and the focal length of the thermal lens itself depends on v_f and T_p, the consequence will be instabilities in the fuse velocity and temperature; they are likely to be periodic in nature (oscillating between permanent and nonpermanent damage). Such large oscillations in T_p will mean that the calculated peak temperature (2113°C for the case in Fig. 1), assuming no thermal lensing, will be much lower than that estimated from the measured reradiated spectrum (roughly 5400°C in Fig. 1). Thus the large disparity in these two temperatures can be explained. We intend to address this question in more detail in a future publication.

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