Core-Clad Silver Halide Fibers for CO_2 Laser Power Transmission

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ABSTRACT

Core-clad optical fibers with efficient IR power delivery are essential components in the development of laser endoscope systems for surgical applications. The fabrication of such clad fibers of high quality is still an unsolved technical problem. We have investigated parameters of the fabrication of core-clad polycrystalline silver halide optical fibers and found conditions that yield fibers with relatively good transmittance at 10.6 μm (about 3 dB/meter loss) and capable of delivering output power densities up to 3 kwatt/cm^2 in CW operation. This performance is lower than what we achieved in core-only silver halide fibers, but the advantage of the protection provided by the clad and a subsequent plastic overcoat, make these core-clad fibers useful in a number of CO_2 power transmission applications in laser surgery.

1. INTRODUCTION

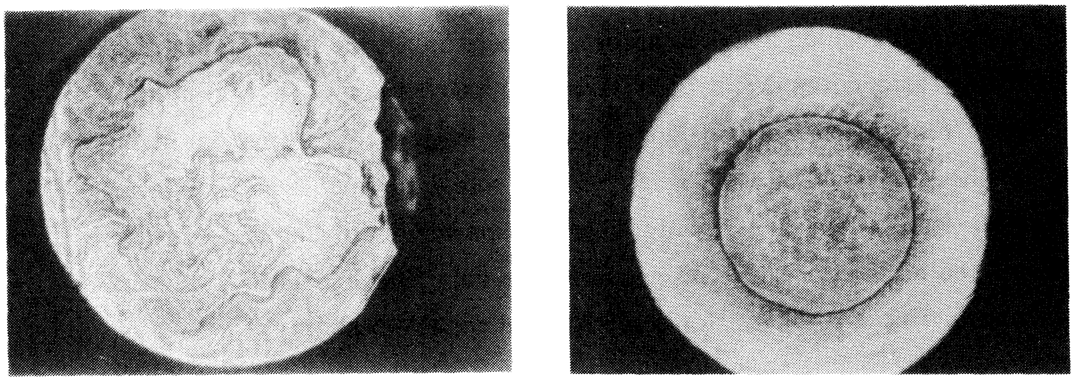
The CO_2 laser is the most common laser for surgery because of its high power, efficiency, low cost and high absorption in living tissue. In order to use this laser for least invasive surgery inside the body there is a need for high power transmitting optical fibers. Progress has been reported recently in both the fabrication of infrared (IR) transmitting optical fibers and their application in infrared spectroscopy, radiometry, and high power laser delivery in industrial and medical applications [1,2].

0-8194-0510-8/91/$4.00

IR fibers based on polycrystalline silver halide mixed crystals ($AgCl_xBr_{1-x}$) are among the leading candidates for most of these applications because of their wide transparency range, high flexibility, non toxicity, and insolubility in water [3,4]. A few groups have developed high power IR transmitting crystalline fibers using the extrusion technique, but none of them have convincingly demonstrated the possibility of practical applications of such fibers. The main "bottleneck" for such use is the absence of core-clad fibers of adequate quality [5-7]. To date, most reports of high quality fibers, including those of our group, have referred to core-only structures. Such fibers are not well suited for routine surgical and industrial applications because of handling sensitivity due to evanescent wave absorption, and high angular spread of the output beam. In core-clad fibers a tight coating can be applied on the outer clad surface to give mechanical and chemical protection and improve the heat dissipation from the fiber. A core-clad structure also has the advantage of a smaller numerical aperture (NA) and the possibility of coherent light delivery.

2. FABRICATION OF CORE-CLAD FIBERS

The fibers are fabricated by extrusion of a "rod in tube" preform [8]. By choosing the concentration ratio between the Cl and Br in the $AgCl_xBr_{1-x}$ we can obtain any value of the crystal refractive index between 1.98 (AgCl) and 2.25 (AgBr), making it possible to obtain any numerical aperture between zero and one. The preform is prepared from a polished rod (core material) inserted in a hollow cladding cylinder of lower bromine concentration. This preform is then extruded through a conical die forming a fiber 2 meters in length, 0.9 mm outer diameter, and 0.3-0.6 mm core diameter. The main problem in the extrusion process is the maintenance of a smooth and circular interface between the core and the clad throughout the deformation. Silver halide crystalline material has an intrinsic tendency to flow inhomogeneously with irregular deformation bands which can be revealed by etching. This deformation behavior leads to an irregular "star like" core-clad interface as shown in Fig. (1.a). With proper conditions, we have managed to eliminate such deformation bands and obtained a homogeneous flow, thus maintaining a circular core with a much smoother interface, as shown in Fig. (1.b). The handling of these fibers was made easier by applying a shrinkable plastic tube jacket which gives better mechanical strength and filters out ambient UV radiation.



(a) (b)

Fig.1. Cross sections of core-clad silver halide fibers fabricated by (a) inhomogeneous extrusion conditions, and (b) homogeneous flow conditions. The fiber face is etched with a solution of sodium thiosulfate.

3. POWER DELIVERY

The measured optical loss for the core-clad fibers is about 3 dB/meter at 10.6 μm. An uncooled, uncoated core-clad fiber of more than one meter in length and 0.45 mm core diameter can transmit 5 Watts CW output power for a few minutes and about 1 Joule in 10 msec CO_2 laser pulses. With a plastic shrinkable tube coating, the numbers are usually smaller because of excessive heating of the entrance. A core-only fiber of 0.9 mm diameter can transmit more than 30 Watts CW. The power delivery by core-clad fibers, as well as core-only fibers, is limited by the damage threshold of the fiber ends which is in the range of 20 to 40 watts. The input face usually damages first in fibers of relatively low transmittance, and it is possible to appreciably increase the damage threshold by cooling the input section of the fiber by a flow of air. Away from the fiber ends, the temperature rise caused by a propagating laser pulse depends on the absorption and the heat capacity per unit length. For a typical silver halide fiber of 0.9 mm diameter, the temperature rise ΔT in ^0C is given approximately by the relation:

$$\alpha_{abs} E = 5.5 \Delta T \quad (1)$$

where α_{abs} is the attenuation caused by absorption in dB/meter, and E the pulse energy in joules. This relation assumes uniform temperature in the fiber and no heat dissipation to the surrounding. From Eq.(1) it is clear that even a poorly transmitting fiber does not heat much at moderate powers as long as there are no highly absorbing localized regions. Since the core area of a core-clad fiber is about a factor of four smaller than a typical core-only fiber, the power density at the output is comparable to the maximum values we get in a core-only fiber (about 3 Kwatt/cm^2 in CW operation). This is sufficient for many surgical applications.

4. OPTICAL PROPERTIES

The near-field power distribution at the exit face of these fibers was measured by a beam-scanner (Photon Inc. Model 1080-20) and was compared to the near field of core-only fibers of the same diameter. The laser radiation was focused by a ZnSe lens of 13 cm focal length on the core center at the input end. Fig.(2) shows the typical power distribution of both a one meter core-clad and a core-only fiber. It is clear that the radiation is totally concentrated in the core of the clad fiber. Enlarged images of the output face with a thermal camera also showed that if the input beam is focused on the fiber core, there is no noticeable radiation escaping into the clad.

In Fig.(3.a) we plot the transmittance of a core-clad fiber immersed in 40 cm of water as a function of the incident angle θ between the incoming laser beam and the fiber axis. At each angle we focused the beam on the fiber input end using a lens of 13 cm focal length, and then moved the fiber entrance slightly to get maximal output power. The same measurement on a core-only fiber is shown in Fig.(3.b). It can be seen that the evanescent wave absorption in the core-only fibers reduces the transmittance of the wet fiber drastically, while the transmittance of the core-clad fibers is practically unchanged. These results imply that a core-clad fiber is not affected by absorbing surroundings. The figures give only qualitative information about the relation between loss and the ray angle because there is strong mode coupling which changes the rays angular distribution along their propagation axis. The allowable field of view (FOV) of the core-clad fiber is much smaller than its numerical aperture. We relate this to large surface scattering losses at high angles.

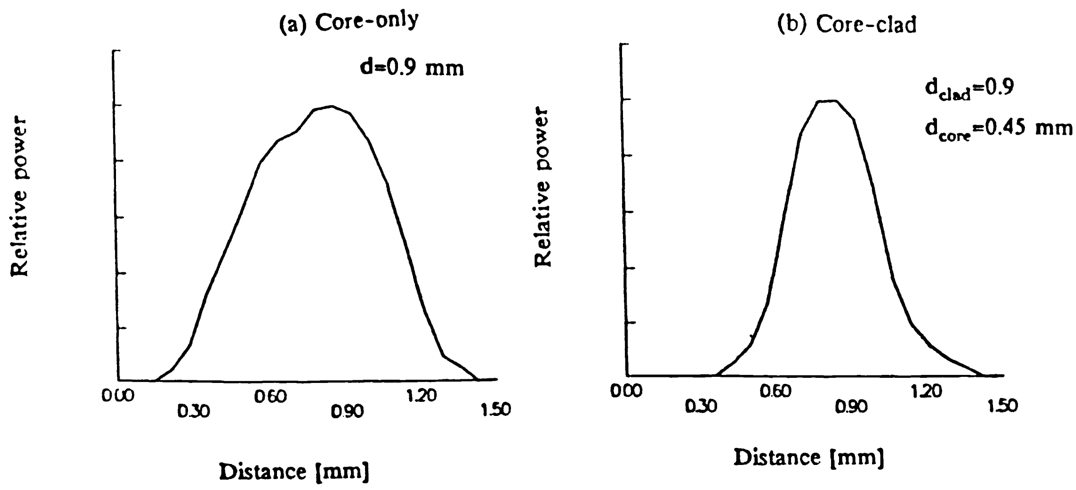


Fig.2. The power distribution on the exit face of (a) core-only and (b) core-clad fibers, measured by an IR beam-scanner (Photonic Inc. model 1080-20).

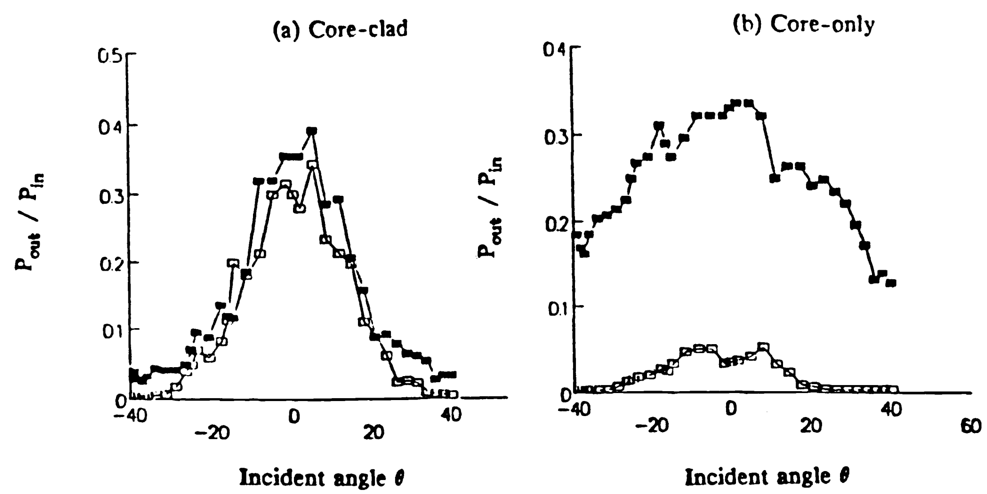


Fig.3. The transmittance of straight fibers in dry air (■) and in 40 cm of water (□) as a function of the incident angle θ of a CO_2 laser beam. (a) core-clad fiber, and (b) core-only fiber.

The beam shape far from the fiber exit was also examined. The CO_2 laser beam was focused on the fiber input end by a concave mirror of 9 cm focal length and at an incident angle θ varying from 0^o to 25^o. The exiting beam was measured using liquid crystal sheets (Edmund Corp. 40-45 ^oC) at a distance of 5 cm from the exit end. The power distribution can be easily obtained from the spot shape on the sheet at various input power levels. We compared the far-field power distribution of a 1.2 meter core-clad fiber of NA about 0.7 with a 1.1 meter core-only fiber. We found that the angular width of the far field power distribution for θ=0 is about 25^o in both fibers. For nonperpendicular incidence ($\theta > 0$) the fibers behave differently. In the core-only fiber the ray angle θ is maintained throughout the propagation, and the exiting beam has a ring-like shape on the sheet. In the core-clad fiber there is strong ray coupling and high attenuation for rays of large angles, so eventually the transmitted power propagates in rays with small θ, giving a concentrated beam shape centered at zero angle.

The optical properties of core-clad fibers depend on the refractive index difference (Δn) between the core and the clad, the core diameter d, and on undesired irregularities in the fiber. The measured optical loss for these fibers (about 3 dB/meter at 10.6 μm) is larger than that observed in our core-only fibers [9]. This increased loss may be due to scattering from the core-clad interface roughness, and/or higher absorption caused by impurities or defects. The core-clad interface is rougher then the outer surface of our core-only fibers because the latter is in effect smoothed by the faces of the diamond die. The roughness usually appears only in small sections of the core-clad interface, as shown in Fig. (1.b). Excess impurities may be introduced by the mechanical handling of the preform and contamination during the complex extrusion.

5. CONCLUSIONS

We have fabricated silver-halide core-clad fibers of more than one meter in length and shown that they can transmit power levels of about 5 watts of CO_2 laser radiation, CW, without excessive heating. Such power levels, combined with the mechanical and chemical protection afforded by a tight plastic overcoat, make these fibers practical for some medical applications, including power delivery in laser endoscopes for surgical operations inside the body. The measured loss of these fibers is about 3 dB/meter. This relatively high loss is mainly due to scattering from the core-clad interface roughness and the excess of impurities, but we assume that with improvements in the fiber fabrication process, the loss may be reduced to levels observed in the core-only fibers - an order of magnitude lower.

6. ACKNOWLEDGMENT

This research was supported by a grant from the United States-Israel Binational Science Foundation (BSF), Jerusalem, Israel.

7. REFERENCES

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