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Ultra-large mode area microstructured core chalcogenide fiber design for mid-IR beam delivery

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ABSTRACT

An all-solid large mode-area (LMA) chalcogenide-based microstructured core optical fiber (MCOF) is designed and proposed for high power handling in the mid-IR spectral regime, covering the entire second transparency window of the atmosphere (3–5 μm). The core of the proposed specialty fiber is composed of a few rings of high index rods arranged in a pattern of hexagon. Dependence of effective mode area on the pitch and radius of high index rods are studied. Ultra-high effective mode area up to 75,000 μm^2 can be achieved over this specific wavelength range while retaining its single-mode characteristic. A negligible confinement loss along with a low dispersion slope ($\sim$0.03 ps/km-nm^2), relatively low bend loss, and a good beam quality factor ($M^2 \sim 1.17$) should make this LMA fiber design attractive for fabrication as a potential candidate suitable for high power, passive applications at the mid-IR wavelength regime.

1. Introduction

The mid-infrared (mid-IR) wavelengths ($\sim$2–10 μm) have recently become increasingly important due to their potential applications in areas as wide as astronomy, climatology, civil, medical surgery, military, biological spectroscopy, semiconductor processing, optical frequency metrology, optical tomography and sensing [1–5]. This has opened up a wide interest in the development of optical fibers that can efficiently generate mid-IR light [6–10] and passive fibers for high power delivery [11–14]. LMA fibers are very attractive for guiding and delivering high laser power because of enhanced threshold power limit for material damages to occur. Additionally, its relatively wider core significantly reduces fiber non-linear effects like Stimulated Brillouin Scattering (SBS) inside the fiber along its length. Moreover, low numerical aperture (NA) LMA fibers are very effective in reducing the amplified spontaneous emission (ASE). On the other hand, as an active medium, LMA fibers are widely used to amplify intense pulses of single frequency signals [15]. It is well known that the overall dispersion behavior of such LMA fibers is mainly dictated by the nature of the chosen materials. Thus, for any design of mid-IR LMA fibers, fiber materials should be very carefully chosen. Material should be chemically stable, sufficiently transparent in the desired spectral range, possess low propagation loss, and are drawable in fiber form. Chalcogenide glasses (S–Se–Te based glass compositions) match almost all the above-mentioned criteria, and hence are strong candidates for realizing mid-IR optical fibers. In addition, their chemical durability, glass transition temperature (T_g), strength, stability etc can be modified appropriately by doping with As, Ge, Sb or Ga, thereby making them suitable for drawing into an optical fiber. Though expensive their state-of-the-art fabrication technology is also well matured [5,16–19] for realizing application-specific specialty fibers for the mid-IR wavelengths.

Various attempts have already been made to realize LMA fibers based on higher order mode (HOM) guiding fibers, in which large differential loss is induced between the fundamental mode (FM) and the HOMs. For example, in a leaky channel fiber, or hollow and solid core MOFs, or in Bragg fibers, or differential gain guiding in multi mode fibers – in all of which differential confinement loss/bend–loss can be exploited to realize effective FM operation [11–14,20–22]. Most of these already reported design philosophies revolve around specifically targeted applications. In the context of LMA fiber designs, discrete photonic structures have recently opened up a novel design route to fulfill the task of LMA with better design freedom in controlling the optical properties of the mode and for further up-scaling of the mode size [23–24]. Our present fiber design consists of a microstructed core in place of a uniform refractive index core.

In this paper, our primary goal is to design a chalcogenide glass-based, microstructured-core LMA fiber for high power delivery at the 3–5 μm wavelength regimes. Single-mode operation over this targeted spectral range is confirmed by maintaining the

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effective V number of the suitably structured core within the single-mode limit. Dependence of effective mode-area (A_{eff}) on various fiber parameters has been studied to achieve A_{eff} as high as 75,000 μm^2 while maintaining very low confinement loss and a good beam quality factor ($M^2 \sim 1.17$). In our proposed fiber design route to optimize the low loss, ultra large mode area fiber with the above-mentioned good beam quality, we have essentially synthesized two different categories of optical systems: a conventional total internal reflection guided fiber structure and a discrete photonic structure.

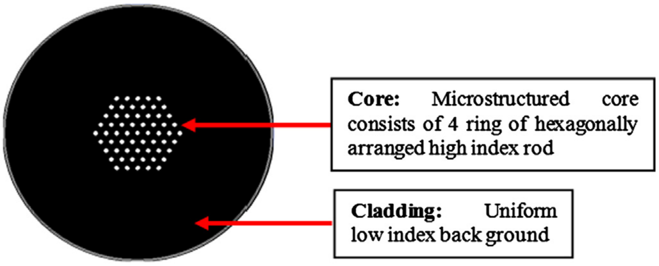

Fig. 1. Transverse view of the proposed LMA fiber. Microstructured core (white circles) consisting of 4 rings of hexagonally arranged $As_{20}Se_{80}$ rods are embedded at the center in $Ge_{12.5}As_{20}Se_{67.5}$ (shown in black), which also forms the cladding.

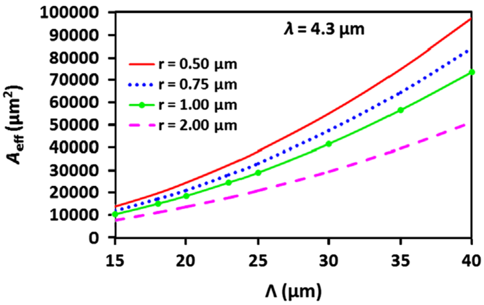

Fig. 2. Variation of mode effective area of FM with pitch (Λ) for 4 different values of radius of high index rod (r) as the labeling parameter.

2. Proposed fiber design and numerical simulations

Mode effective area A_{eff} of a fiber can be increased either by increasing the core diameter (d) or by decreasing the NA. Increase in d makes the fiber multimoded; on the other hand due to limitations in doping level of refractive index modifiers in a high-silica based fiber, NA in conventional fibers is hard to reduce to sufficiently small values for this purpose. In our design, we could significantly reduce the NA through an effective decrease in core refractive index (n_c). Instead of using a large uniform core with conventional microstructured cladding, we considered a microstructured core embedded in a material, which also formed the cladding of uniform low index. The cross section of the proposed fiber design is shown in Fig. 1. The microstructured core of the fiber consists of 4 rings of hexagonally arranged high index circular rods of chalcogenide glass $As_{20}Se_{80}$, whose refractive index (n_r) at 4 μm wavelength is ~2.575. The radius of each high index rod is denoted as r and the center to center spacing between two nearest rods i.e. the pitch is denoted as Λ. Cladding forms the uniform low index background made out of chalcogenide glass composition, $Ge_{12.5}As_{20}Se_{67.5}$, whose refractive index (n_b) at 4 μm is ~2.565. Thus the core, consisting of these two chalcogenide glasses, effectively reduces n_c below fabrication limit and hence yields an ultra-high A_{eff}.

The simulation results were obtained through use of the freely available software CUDOS® based on Multipole Method, which were also verified by full vectorial finite element method. The structure was optimized with 4 rings of high index rods for SM operation. The mode effective area was calculated by using the following standard formula

$$A_{eff} = \frac{(\int EE^* dA)^2}{\int (EE^*)^2 dA} \tag{1}$$

where E and E^* represents the electric field and its complex conjugate, respectively.

Dependence of A_{eff} of the fundamental mode (FM) on the microstructured core parameters r and Λ is studied and the same is shown in Fig. 2. From this figure it is evident that A_{eff} gradually

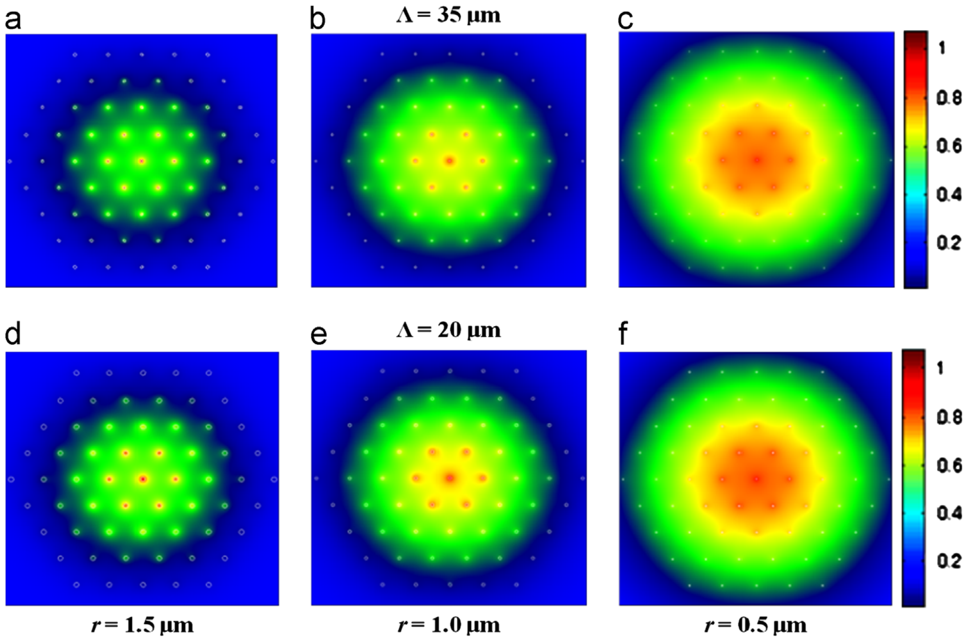

Fig. 3. Fundamental mode pattern at $\lambda = 4.3$ μm. (a) $r = 1.5$ μm and $\Lambda = 35$ μm; (b) $r = 1.0$ μm and $\Lambda = 35$ μm; (c) for $r = 0.5$ μm and $\Lambda = 35$ μm; (d) $r = 1.5$ μm and $\Lambda = 20$ μm; (e) $r = 1.0$ μm and $\Lambda = 20$ μm; and (f) for $r = 0.5$ μm and $\Lambda = 20$ μm.