Flexible single-mode delivery of high power 2 μm pulsed laser using antiresonant hollow-core fiber

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We demonstrate flexible single-mode transmission of a high average power 2 μm nanosecond pulse using antiresonant hollow core fibers (AR-HCF). 39.1 W average power is delivered using a coiled 1.7 m AR-HCF, which is designed for single-mode guidance and good higher-order mode suppression. The effect of bending on the fiber output power and beam profile is also investigated. The Gaussian-like output beam profile is maintained up to 7.5 cm bending radius. This is the highest average power delivered by a flexible long HCF in this wavelength without the need for an enclosed controlled environment, to the best of our knowledge. © 2018 Optical Society of America

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Lasers operating at the wavelength of 2 μm are useful for medical surgery, material processing and spectroscopy due to the inherent absorption of various molecules and molecular bonds of interest at this wavelength. The delivery of high power laser light may be done through free-space bulk optics, which lack flexibility. Therefore, a more attractive alternative to deliver the laser light is through optical fibers, which offers flexibility and maneuverability.

Ideally, the delivery fiber should maintain or even improve the beam quality, with low losses. However, conventional solid core fibers are susceptible to material absorption losses and thermal effects, limiting their ability to transmit high average power infrared light. The small core coupled with the high nonlinearities associated with solid materials, makes solid core fibers susceptible to nonlinear effects when transmitting pulses while maintaining single mode guidance. Furthermore, larger core sizes increase bending sensitivity and thus sacrifice the flexibility of the fiber [1].

The solution is to use the hollow-core fiber (HCF), where light is guided within the air/vacuum core region. Photonic bandgap HCFs show potential for flexible pulse delivery, however the core sizes are typically small (<30 μm) to maintain single-mode guidance, which renders coupling more difficult [2]. Another strategy to achieve single-mode guidance in PBG HCFs is to introduce shunt

side cores requiring complex fabrication [3]. Bragg hollow fibers on the other hand, are limited by the bending losses and fabrication complexity (to control the cladding layer thickness and/or refractive indices) to achieve single-mode guidance [4].

Antiresonant HCFs (AR-HCFs) are a type of HCFs emerging recently having low losses yet broad transmission bands [5]. The thin layer of core wall is regarded as a Fabry-Perot resonator at the glazing incidence and at off-resonance wavelengths, the multiple-beam-interference reflects most of the light back to the core and results in a low leakage loss. The other key advantage of AR-HCF is the ability to maintain single-mode guidance at core sizes which are typically multi-mode in nature for other fibers. The large-core design and negative-curvature core boundary significantly reduce the modal overlap with the fiber material in the cladding, which make AR-HCFs ideal for ultrafast pulse delivery due to the lower nonlinearity, lower dispersion and much higher damage threshold [5]. Minimized material absorption and thermal effects show the potential of AR-HCFs for high average power delivery.

The use of AR-HCFs for high energy μs pulses at 2.94 μm have been reported at low repetition rates (1-10Hz), and consequently at low average powers [6]. Picosecond and nanosecond pulse delivery at 1 μm wavelength using similar structured AR-HCF have also been reported, albeit with a multimode and unstable beam output [7]. AR-HCFs have also been used as gas-filled compressors, achieving an output power of 43 W at 1.82 μm central wavelength, using a straight 42 cm length of fiber enclosed in an argon-filled gas chamber [8].

In this Letter, we investigate the use of AR-HCF for flexible single-mode high average power delivery of 2 μm nanosecond pulses. The delivery of high average power 2 μm light is challenging due to water absorption causing the thermal blooming effect, which degrades the beam profile quality [9]. Here, we show the 1.7 m coiled fiber with a 48 μm core could deliver up to 39.1 W with excellent Gaussian-like beam quality. The setup was done in ambient laboratory conditions, without the need for an enclosed controlled environment. The thermal blooming effect was mitigated by the good confinement qualities of the AR-HCF, coupled with the center wavelength selection of the source to be further away from the water absorption peak. This is the highest average power delivered by a >1 m long AR-HCF in this wavelength regime, to the best of our knowledge.

The AR-HCF used in this paper has its negative curvature core bounded by a single ring cladding structure, which consists of 7 touching “ice-cream cone” capillaries as shown in Fig. 1. The measured fiber parameters are listed in Table 1. The mode analysis was done by finite-element method (FEM) using COMSOL Multiphysics, with the fiber structure depicted in Fig. 1(b). The calculated attenuation is shown in Fig. 1(c). The measured attenuation was obtained by the cut-back method.

The simulation predicts the fiber transmission band edge and attenuation within transmission band around 2 μm ; there are discrepancies due to the fabrication asymmetry and variations of the capillary wall thickness. Fabrication asymmetry resulting in variations of the cladding diameters and an off-center core was not reflected in the simulated fiber structure, causing the actual measured attenuation within the transmission band to be higher than simulated. The curved and straight sections of the capillary have thicknesses of $1.429 \pm 0.011 \mu\text{m}$ and $1.365 \pm 0.013 \mu\text{m}$ respectively, whilst the capillary thickness was set at $1.365 \mu\text{m}$ in the simulation. The simulation was re-run (not shown here) with the wall thickness set at $1.43 \mu\text{m}$, and the losses reach 1 dB/m at 2200 nm as compared to 2425 nm for $1.37 \mu\text{m}$ thickness. Thus, the variations in the wall thickness caused the discrepancies in the transmission band edges. The discrepancies at the longer wavelengths ($>2 \mu\text{m}$) were also due to the glass material absorption which was not considered in the simulation.

Fig. 1. (a) Scanning electron microscope (SEM) image of the AR-HCF; (b) AR-HCF structure simulated in COMSOL; (c) Measured and simulated attenuation spectra of the fundamental mode; Inset: fundamental mode from FEM simulation.

Table 1 AR-HCF properties

Fiber properties	Values
Fiber diameter, (μm)	220
Core diameter, d_{core} , (μm)	48
Capillary diameter, d_{cap} , (μm)	32
Capillary wall thickness, (μm)	1.37
Numerical aperture	0.038

The seven-cell AR-HCF has been shown to have better higher-order mode (HOM) suppression than the 6-cell and 8-cell counterparts. The HOM suppression design principle is to phase-match the propagation constants of the fundamental modes in the capillary cladding to that of the higher-order mode in the core [10]. This was done by controlling the ratio between the core and cladding diameter. The transmission bands of AR-HCFs have been found to be related to the capillary wall thickness. Hence, this AR-HCF was designed for single-mode guidance, with excellent HOMs suppression around the 2 μm wavelength regime [10-12].

For the beam delivery demonstration, a 1.7 m AR-HCF was used. The fiber was coiled one full round with varying bending diameters in the setup. A short 3-4 cm portion of the fiber input end was stripped bare and then recoated with a UV-cured polymer (Luvantix PC-515 HT) for thermal management purposes. The in-house built fiber laser source provides 1.2 ns pulses at a maximum average power of 60W, of 65 MHz repetition rate at 1980 nm wavelength [13]. Note that the pulse is highly chirped, hence its nanosecond pulse nature despite having a broad spectral width.

Fig. 2. Beam delivery setup schematic; Insets: (Left) Beam profile of fiber laser source, (Right) Beam profile of AR-HCF output; PM – power meter, HR – high-reflection, AR PCX – anti-reflection plano convex, BD – beam dump, PBS – polarizing beam splitter, HWP – half waveplate, TFP – thin film polarizer

The beam is directed to the AR-HCF by a pair of high-reflection (HR) mirrors and focused by a single anti-reflection coated plano convex (AR PCX) lens (diameter = $\frac{1}{2}$ ", $f = 25 \text{ mm}$). Translational stages and a mirror pair were used to optimize the alignment of the laser beam reaching the fiber. The input end of fiber (8 cm length) was mounted on a copper groove, which was then mounted on an aluminum heat sink block, with no additional active cooling. The entire beam delivery setup is depicted in Fig. 2 and is done in ambient laboratory ($50 \pm 2\% \text{ RH}$ at 20°C) conditions without the need for reduced pressure, extreme low humidity or purging in an enclosed chamber.

The AR-HCF output was measured right after the collimating lens. The transmission efficiencies were recorded at different input powers up to 60 W as shown in Fig. 3. The transmission efficiency here refers to the ratio between the AR-HCF output power measured and the input power measured before the HR mirror pair.

The source output beam profile (measured at the same distance as the AR-HCF focusing lens) and AR-HCF output beam profiles at 10 W, 30 W and 60 W input powers are also shown in Fig. 3. The AR-HCF output beam profiles along the x and y-axis were plotted in Fig. 3(c) to show the excellent Gaussian-like beam quality at 60 W input power. All beam profile measurements were done after

attenuation using polarization free-space optics (depicted in Fig. 2) to avoid damaging the beam profile camera.

The input beam and AR-HCF output beam properties are listed in Table 2. The input beam has a slight asymmetry, which may have limited the maximum transmission efficiency. The transmission efficiency also decreased significantly from 76.0 % at 30 W input power to 65.2 % at 60 W input power. The 1.7 m long fiber was undamaged by the maximum available laser power of 60 W.

Fig. 3. (a) The transmission efficiency and (b) beam profiles at various input powers. The AR-HCF was coiled one full round with a bending diameter of 30 cm; (c) Beam profiles along x and y-axis at 60 W input power

Table 2 Input beam and AR-HCF beam measurements obtained using the beam profiling camera

Input power (W)	Input beam properties		AR-HCF output beam properties	
	Diameter, x by y (mm)	Effective diameter (mm)	Diameter, x by y (mm)	Effective diameter (mm)
10	1.971 x 2.364	2.215	2.753 x 2.816	2.745
30	1.727 x 2.064	1.907	2.394 x 2.379	2.435
60	1.456 x 1.714	1.571	2.404 x 2.390	2.334

The effective beam diameter measured at 10 W input power was 2.22 mm which decreased to 1.57 mm at 60 W input power. The decrease in the input beam diameter cause the focal spot size at the fiber input end to increase by 41%, and thus resulted in the

decrease in transmission efficiency. The source output collimating lens was found to heat up to 70°C at 50 W using a thermal imaging camera, due to the lens material absorption. Thus, the decrease in the beam diameter at both the source output and AR-HCF output collimating lens may be attributed to thermal expansion effects in the lens during high power operation, which decreases the lens focal length. In future, the silica-based lens will be replaced with calcium fluoride lens, to minimize material absorption and thermal effects.

A polarizer and waveplate was further added before the coupling lens to adjust the power entering the fiber without changing the laser output power and thus without changing the input beam size. The transmission efficiencies obtained deviated less than 1%, further confirming the effect of the input beam diameter on the transmission efficiency. The highest transmission efficiency was ~77 %, which may be limited by the poor spatial beam quality of the input beam.

The critical bending diameter for the fundamental mode, approximated using the analytical solution for a single-ring hollow core fiber, is from 8.1 to 12.9 cm, depending on the angle between the fiber orientation and the bending plane [14]. We then experimentally investigated the effect of bending, by varying the coil bending diameter from 15 to 35 cm, at 5 cm intervals (input power at 30 W). There was negligible loss (<1%) when the fiber was bent from 35 cm to 20 cm diameter. At 15 cm bending diameter, there was a 5.3% loss in average power as compared to the output power with 35 cm bending diameter. The output beam maintained its good beam quality in all the bending diameters measured as detailed in Fig. 4.

Fig. 4. (a) Input beam profile at 30 W, and (b-d) the AR-HCF output beam profile at different bending diameters; (e) Transmission loss vs. bending radius

The spectrum of the input beam and the AR-HCF output beam were measured by an optical spectrum analyzer, by using a wedge for attenuation and another lens to focus into a 105/125 multi-mode fiber patch cable. There were no new frequencies generated after propagating through the AR-HCF at input power of 50 W as shown in Fig 5. The spectral ripples observed in the input spectrum and AR-HCF output spectrum may be due to modal interference and aperturing effect from the multi-mode patch cord cable [15].

Fig. 5. Input beam and AR-HCF output beam spectra

In this Letter, the maximum input power of 60 W was limited by the source. The duration of delivery at 60 W was approximately 5 mins, to prevent the source pump diodes from overheating. The duration at 50 W was done for at least 30 mins, and no fiber damage was observed for all the results reported here using the same fiber. The authors encountered fiber failure when the coupling efficiency is poor; the acrylate jacketing absorbs the escaped light and burns causing fiber failure. This can be mitigated by better coupling and active thermal management, extending the average power handling capability of the fiber.

Picosecond pulse delivery of a 50 mW, 1950 nm commercial laser source (AdValue Photonics AP-ML1) using a 9 m-long coiled AR-HCF was demonstrated as well. The pulse duration was measured using second harmonic generation frequency-resolved optical gating (FROG) before and after transmission through the AR-HCF. The FROG-retrieved temporal profile is shown in Fig. 6 below, and the pulse width were 1.12 ps and 1.07 ps respectively; the FROG trace error are 0.65% and 0.79% respectively. Thus, the AR-HCF shows potential for flexible delivery of picosecond pulses, owing to its low dispersion properties.

Fig. 6. Input and AR-HCF output pulse temporal profile using commercial picosecond laser source

In conclusion, we have demonstrated flexible delivery of 2 μm laser using a coiled AR-HCF with an output of 39.1 W, with good output beam quality. This is the highest average power delivered using a coiled AR-HCF in this wavelength, to the best of our knowledge. The beam delivery setup did not require active cooling (up to 60 W input) and was done in ambient laboratory conditions. The input laser beam was focused into the AR-HCF core using a single plano-convex lens, demonstrating the ease of coupling. Also, the AR-HCF improved the beam quality, without significant losses; the transmission efficiency was as high as 76% at input power of 30 W. We did not observe any damage on the fiber facet end at the input power of 60 W. We also show that the AR-HCF can deliver picosecond pulses without pulse broadening, due to its low dispersion properties.

During high power transmission, the fiber did not introduce any spectral broadening, which is desirable for beam delivery. The effect of bending on the fiber was also investigated, and there was no beam quality degradation at all the bending diameters tested. There was a 5.3% loss in average power when the fiber was coiled to 15 cm diameter as compared to 35 cm diameter. Our findings also show that this AR-HCF can improve the beam quality, maintaining a Gaussian-

like beam at the output even though the input beam is asymmetrical. A good beam quality is necessary for consistent and good quality material processing, whether for precision machining applications or in laser surgery. The AR-HCF is also robust and maintained its beam quality even when bent to 15 cm diameter, which makes it an excellent candidate for flexible and maneuverable beam delivery. The high average power handling demonstrated here, showcases the fiber's capability for high average power HCF-based nonlinear pulse compression configurations.

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