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Impact of nonlinear effects on transmission losses of hollow-core anti-resonant negative-curvature optical fiber

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Abstract: We investigate the impact of input pulse duration and peak power of a femtosecond laser on pulse broadening and propagation losses in selected hollow-core anti-resonant fiber (HC-ARF). The mixed effects of strong self-phase modulation and relatively weak Raman scattering broaden the spectral width, which in turn causes a portion of the output spectrum to exceed the transmission band of the fiber, resulting in transmission losses. By designing and setting up a gas flow control system and a vacuum system, the nonlinear behavior of the fiber filled with different pressurized gases is investigated. The experimental results show that replacing the air molecules in the fiber core with argon can weaken pulse broadening and increase the transmittable peak power by 14 MW for a given 122 MW input, while a vacuum system can reduce the nonlinearity to a larger extent, therefore enhancing the transmission of HC-ARF by at least 26 MW. © 2015 Optical Society of America

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1. INTRODUCTION

With recent technical advances and commercialization of reliable high average-power picosecond and femtosecond lasers at reasonable cost, they have become widely used for industrial applications e.g. micro-machining [1], medical treatments [2] or laser microscopy [3]. However, flexible delivery of high-power laser pulses can still be an issue restricting the development of ultrafast laser applications. The increasing demand for higher power pulses prevents the use of solid core optical fiber, mainly due to the relatively low damage-threshold of glass, although non-linearity is also an issue. To overcome these limitations, hollow-core optical fibers have been developed [4-6], in which the core region is mainly filled with a gas or a vacuum, thus providing a significantly higher damage threshold and ultra-low nonlinearity. Unlike the total internal reflection guidance principle of a solid core fiber, hollow core fibers guide light in a low refractive index core region by introducing complex cladding structures.

In the hollow core fiber family, photonic bandgap fibers (PBGFs) provide very low losses, e.g. 1.7 dB/km at 1620 nm [7]. They can also provide high damage threshold [8]. However, due to the shape of the fiber structure the area of overlap between the core fundamental mode and the glass structure is relatively large, so the damage threshold of PBGFs may limit their use [9]. On the other hand, in the negative-curvature hollow core anti-resonant fibers (HC-ARFs) the overlap between the core mode and the glass structure is extremely small due to the negative curvature of the glass resonance layer in regards to the core area. In addition, their core sizes are typically larger than those of PBGFs, what in combination with small overlap area significantly increases their damage threshold over PBGFs [10]. Moreover, HC-ARFs can demonstrate very low attenuation, even lower than that of PBGFs, in the industrially used 1 μm wavelength region, while also possessing wider transmission windows than the latter [11,12]. Therefore HC-ARFs can be considered in the near-infrared region to be the most suitable fibers for high-power beam delivery [13-16]. However, a sudden decrease in output power can be observed for ultrashort laser pulses over a certain peak power, likely due to nonlinear interactions of light with air molecules in the fiber core.

In this paper, we explain for the first time to our knowledge the mechanism that causes this transmission loss in anti-resonant negative-curvature fibers by measuring and analyzing the output spectra of ultrashort pulses. Gas filling and evacuation of the fiber were experimentally carried out for the purpose of nonlinearity reduction. The effects of these two methods on reducing nonlinear effects and power transmission loss in an HC-ARF are first compared and discussed to our knowledge.
2. INVESTIGATED FIBER

The HC-ARF investigated in this paper is an “ice-cream cone-shaped” fiber (so-named due to the similarity of the cladding structures to a circular array of ice-cream cones) with 7 capillaries, core size of 25 μm, numerical aperture (NA) 0.044 and 850 nm thick glass walls (Fig. 1(a)). The region of glass closest to the core (the anti-resonant layer) curves away from the center of the core (negative-curvature), decreasing the overlap area between the core mode and the glass, thereby reducing the material loss of the fundamental mode and increasing the damage threshold of the fiber. Previously reported measurements on HC-ARF transmission performance showed that the fiber has performed well in both laser micromachining [17] and medical applications [18] at a wavelength of around 1 μm. The HC-ARF investigated in this paper is an “ice-cream cone-shaped” fiber (so-named due to the similarity of the cladding structures to a circular array of ice-cream cones) with 7 capillaries, core size of 25 μm, numerical aperture (NA) 0.044 and 850 nm thick glass walls (Fig. 1(a)). The region of glass closest to the core (the anti-resonant layer) curves away from the center of the core (negative-curvature), decreasing the overlap area between the core mode and the glass, thereby reducing the material loss of the fundamental mode and increasing the damage threshold of the fiber. Previously reported measurements on HC-ARF transmission performance showed that the fiber has performed well in both laser micromachining [17] and medical applications [18] at a wavelength of around 1 μm. The HC-ARF investigated in this paper is an “ice-cream cone-shaped” fiber (so-named due to the similarity of the cladding structures to a circular array of ice-cream cones) with 7 capillaries, core size of 25 μm, numerical aperture (NA) 0.044 and 850 nm thick glass walls (Fig. 1(a)). The region of glass closest to the core (the anti-resonant layer) curves away from the center of the core (negative-curvature), decreasing the overlap area between the core mode and the glass, thereby reducing the material loss of the fundamental mode and increasing the damage threshold of the fiber. Previously reported measurements on HC-ARF transmission performance showed that the fiber has performed well in both laser micromachining [17] and medical applications [18] at a wavelength of around 1 μm. The HC-ARF investigated in this paper is an “ice-cream cone-shaped” fiber (so-named due to the similarity of the cladding structures to a circular array of ice-cream cones) with 7 capillaries, core size of 25 μm, numerical aperture (NA) 0.044 and 850 nm thick glass walls (Fig. 1(a)). The region of glass closest to the core (the anti-resonant layer) curves away from the center of the core (negative-curvature), decreasing the overlap area between the core mode and the glass, thereby reducing the material loss of the fundamental mode and increasing the damage threshold of the fiber. Previously reported measurements on HC-ARF transmission performance showed that the fiber has performed well in both laser micromachining [17] and medical applications [18] at a wavelength of around 1 μm. The HC-ARF investigated in this paper is an “ice-cream cone-shaped” fiber (so-named due to the similarity of the cladding structures to a circular array of ice-cream cones) with 7 capillaries, core size of 25 μm, numerical aperture (NA) 0.044 and 850 nm thick glass walls (Fig. 1(a)). The region of glass closest to the core (the anti-resonant layer) curves away from the center of the core (negative-curvature), decreasing the overlap area between the core mode and the glass, thereby reducing the material loss of the fundamental mode and increasing the damage threshold of the fiber. Previously reported measurements on HC-ARF transmission performance showed that the fiber has performed well in both laser micromachining [17] and medical applications [18] at a wavelength of around 1 μm. The HC-ARF investigated in this paper is an “ice-cream cone-shaped” fiber (so-named due to the similarity of the cladding structures to a circular array of ice-cream cones) with 7 capillaries, core size of 25 μm, numerical aperture (NA) 0.044 and 850 nm thick glass walls (Fig. 1(a)). The region of glass closest to the core (the anti-resonant layer) curves away from the center of the core (negative-curvature), decreasing the overlap area between the core mode and the glass, thereby reducing the material loss of the fundamental mode and increasing the damage threshold of the fiber. Previously reported measurements on HC-ARF transmission performance showed that the fiber has performed well in both laser micromachining [17] and medical applications [18] at a wavelength of around 1 μm.

The HC-ARF fiber has a length of 45 m, and the fiber input end was mounted on a XYZ positioning stage for alignment with the incident beam. Two lengths of fiber were used, 2.2 m and 0.65 m, and the total coupling efficiency (fiber throughput) reached 83%. The achieved total coupling efficiency was not limited by either waveguide or material losses. The main loss is due to mode matching error. Additionally, the fiber mounting method we use (clamping or sticking with a magnet) introduces some stress on the fiber tip and that also causes a small initial loss of the signal. In order to monitor changes in transmission, the light output from the fiber was directly measured using a photodiode power meter; and to examine any nonlinear effects, two Ocean Optic spectrometers were used to measure the spectra from the UV through to the near infrared (NIR). One of the spectrometers is the FLAME-S-UV-VIS covering the UV and visible range (303 nm – 1023 nm), and the other, the S2000, is for near infrared (931 nm – 1665 nm) spectral measurement.

The part outside the blue dotted frame in Figure 2 was designed for gas filling experiments. In this case, the output end of the fiber was fixed in a sealed gas cell, and the output beam was received by the spectrometer through a glass window of the gas cell. The gas flowed into the fiber through this gas cell and vented out from the laser-fiber coupling end. During gas filling, the pressure in the gas cell was stabilized at 0.4 bar. The time required to complete the gas filling process was obtained by monitoring the reshaped output spectral profile when the gas was switched from air to argon at the fixed laser parameters (average power 1.94 W; pulse duration 1.5 ps repetition rate 60 kHz). When the output spectral shape no longer changes over time, it indicates that the filling of the new gas has been completed, and this process takes approximately 10 minutes. After the fiber was filled with a new gas, a constant gas flow of 45 standard cubic centimeters per minute (SCCM) was maintained using a mass follow controller.

3. EXPERIMENTS AND DISCUSSION

To test the ability of this fiber to transmit ultrashort laser pulses, we built an experimental setup to compare the characteristics of the input and output spectral, as shown in the blue dashed frame in Fig. 2. The laser source used here is a CARBIDE (LIGHT CONVERSION) laser with a center wavelength of 1028 nm and repetition rate fixed at 60 kHz. Pulse durations in the range 1.5 ps to 230 fs were used, for a maximum average power of 1.94 W, hence the maximum input peak power was 141 MW. The incident angle of the input laser beam was adjusted using two high reflectivity mirrors, and the beam was focused by a 40 mm lens onto the input end face of the fiber. The fiber input end was mounted on a XYZ positioning stage for alignment with the incident beam. Two lengths of fiber were used, 2.2 m and 0.65 m, and the total coupling efficiency (fiber throughput) reached 83%. The achieved total coupling efficiency was not limited by either waveguide or material losses. The main loss is due to mode matching error. Additionally, the fiber mounting method we use (clamping or sticking with a magnet) introduces some stress on the fiber tip and that also causes a small initial loss of the signal. In order to monitor changes in transmission, the light output from the fiber was directly measured using a photodiode power meter; and to examine any nonlinear effects, two Ocean Optic spectrometers were used to measure the spectra from the UV through to the near infrared (NIR). One of the spectrometers is the FLAME-S-UV-VIS covering the UV and visible range (303 nm – 1023 nm), and the other, the S2000, is for near infrared (931 nm – 1665 nm) spectral measurement.

First, the output power versus input power of the pulse was measured in the HC-ARF fiber (Section 3.A). Next, a series of spectra for various conditions of the input pulse were taken in order to determine the reason behind the drop-off in output power (Section 3.B). Finally, the fiber was filled in turn with various gases to investigate the change in the nonlinear behavior of the fiber (Section 3.C), followed by another investigation in a vacuum system (Section 3.D).

A. Transmission drop

It is normally expected that the output peak power of the pulse should increase linearly with the input peak power. However, we
observed that the output peak power shows a tendency to decrease as the input peak power is increased to 115 MW (Fig. 3). Fig. 4 shows the impact of input pulse energy on transmission loss for seven pulse duration levels from 5 ps to 230 fs. When the input pulse duration is shorter than 530 fs, the fiber transmission begins to decrease dramatically. The shorter the pulse width, the faster the transmission drops. In addition, when the input peak power is greater than 40 MW, scattered light of a pale blue color can be observed from the side of the fiber (Fig. 5). Although the nonlinear refractive index $n_2$ of air ($3 \times 10^{-23} m^2/W$) is much lower than that of fused silica ($2.74 \times 10^{-20} m^2/W$) [19], the fiber transmission drop and scattering of light still occur due to the nonlinear effects induced by the interaction of high-peak power pulses with the nitrogen molecules in the air present in the fiber core. Some nonlinear effects can be beneficial e.g. for supercontinuum generation [20], but for most industrial applications the nonlinear behavior of the fiber is only a hindrance.

B. Nonlinear behavior of the fiber

The output spectra from the HC-ARF fiber were measured for input average powers in the range of 0.26 W – 1.94 W and for pulse durations in the range 1.5 ps – 230 fs, giving peak powers in range from 2.2 MW to 141 MW. As the input laser peak power increases from 2.9 MW to 22 MW, the output spectrum measured for a 1.5 ps pulse broadens asymmetrically (Fig. 6). The spectrum shape distorts from a single peak located at the original pump wavelength at 5.7 MW peak power to a multiple-peak spectrum at 22 MW, spanning 64 nm from the initial pump spectral width of 11.6 nm. Also, an unusually strong peak located at the short-wavelength end was observed.

To explain the resulting shape of the spectrum presented in Fig. 6, the concept of fiber dispersion and its impact on the pulse (and further the spectrum) broadening must be explained. Mathematically, the effects of dispersion in a fiber (pulse broadening in time) are accounted for by expressing the mode-propagation constant $\beta(\omega)$ in a Taylor series expansion about the central frequency $\omega_0$, as shown in equations 1 and 2 [21, pp. 8-10].

$$\begin{align*}
\beta(\omega) &= \beta_0 + (\omega - \omega_0) \beta_1 + \frac{1}{2} (\omega - \omega_0)^2 \beta_2 \\
&\quad + \frac{1}{6} (\omega - \omega_0)^3 \beta_3 + \cdots 
\end{align*}$$

(1)

Where
In order to help explain the nonlinear behavior of the HC-ARF fiber, the GVD of the fiber has been calculated based on the model presented by Hasan et al. [22] (Fig. 7(a)). We also present measured transmission of the 45 m piece of the HC-ARF fiber (Fig. 7(b)). Although the calculated resonance band (1.7 µm) indicates that the fiber should transmit beyond 1.35 µm, the decreasing GVD (Fig. 7(a)) makes it weaken its guiding above that wavelength. Additionally, the applied numerical model proposed by [22] has been developed for ARFs with circular capillaries of equal diameter and thickness of the wall, whilst our fiber has an “ice-cream” cone-shaped structure with slightly irregular capillaries (±100 nm variation of the wall thickness). Those factors make the transmission band of the fiber narrower than expected. Nonetheless, the calculated characteristic thickness). Those factors made the transmission band of the fiber slightly irregular capillaries (±100 nm variation of the wall, whilst our fiber has an “ice-cream” cone-shaped structure with slightly irregular capillaries (±100 nm variation of the wall thickness). Those factors make the transmission band of the fiber narrower than expected. Nonetheless, the calculated characteristic provides a qualitative measure of how the dispersion of the fiber changes across its transmission window and provides an approximate GVD value for the pump wavelength. In the case of the HC-ARF fiber the GVD has a low value of 10 fs²/cm for the 1.028 µm pump wavelength. Additionally, the pump wavelength is located close to the steep slope of GVD curve, where β₃ is large. Based on Fig. 7, the zero-dispersion wavelength (ZDW) of the fiber is located approximately at 1.1 µm.

For the 1.5 ps laser pulses (Fig. 6) the broadening of the spectrum occurs due to the self-phase modulation (SPM) effect, i.e. Kerr nonlinearity [23]. As shown in Fig. 7(a) since the pump wavelength is in the low GVD region, but close to the steep slope of GVD at which the third order dispersion β₃ is negative and strong, the SPM-broadened spectrum is distorted towards the blue (in the case of the 22 MW pulse). The presence of a strong third-order dispersion (TOD), along with a weak GVD leads to a strong asymmetrical modulation of the temporal shape of the pulse, which as a result leads to asymmetrical shape of the SPM-broadened spectrum [21]. Depending on the sign of the TOD value, the temporal oscillations will occur either at the trailing edge of the pulse (negative TOD) or at the leading edge of the pulse (positive TOD). In our case, the negative TOD and positive GVD (where shorter wavelengths are slower than longer wavelengths) caused a strong asymmetry of the SPM-broadened spectrum, and most of the energy was transferred to the short-wavelengths end of the spectrum. This resulted in an increased amount of energy transferred outside the transmission window of the fiber and overall decrease in total transmission.

![Fig. 7. (a) Simulated group velocity dispersion (β₂) of the investigated HC-ARF with the laser wavelength highlighted. (b) Measured transmission window of the investigated fiber (45 m in length).](image)

![Fig. 8. Output spectral broadening for a 310 fs pulse in the 2.2 m HC-ARF. The inset replots the data on a different vertical scale to highlight the peaks in the long wavelength region. The blue line in the main graph shows the upper scale limit of intensity of the inset, and the red line indicates the position of the original input laser wavelength of 1028 nm. The light green wavelength area covers the transmission bands of the fiber.](image)

![Fig. 9. Output spectral broadening for the 230 fs pulse in the 2.2 m HC-ARF. The inset replots the data on a different vertical scale to highlight the peaks in the long wavelength region. The blue line in the main graph shows the upper scale limit of intensity of the inset, and the red line indicates the position of the original input laser wavelength of 1028 nm. The light green wavelength area covers the fundamental transmission band of the fiber.](image)
induced strong peaks being generated in both short-wavelength (at 911 nm) and long-wavelength (at 1118 nm) regions. Additionally, part of the energy of the propagating mode has been transferred across the resonant (non-transmissive) band of the fiber to the next transmission band, located at 600~700 nm (Fig. 1(b)).

If the input pulse is further shortened to 230 fs, the effect of SPM becomes more significant and compacts the generated wavelengths into two narrower spectral regions, as shown in Fig. 9. With such intense pulses, some of the photons might be scattered by the air molecules in the fiber core to lower-frequency photons, transiting the molecules to a higher vibrational state, which is described as stimulated Raman scattering (SRS) [21, pp. 298-299]. The effect of SRS can be seen in Fig. 9 inset for pulses with peak power higher than 129 MW in the wavelength region around 1180 nm, where the strong spectral peak is being broadened towards longer wavelengths. The blue-shifted low-intensity group of sharp peaks around 920 nm wavelength in the inset, which appears for both 310 fs and 230 fs pulses (Figs. 8 and 9 respectively), is due to rotational Raman scattering.

Since the lowest order transmission window of the fiber starts at around 920 nm (see Fig. 1(b)), the spectral broadening of the 310 fs and 230 fs pulses that transfers the light further towards the blue results in leakage of energy out of the core because of resonant conditions with the capillary wall. Therefore, nonlinear broadening due to SPM and excessive concentration of energy into the short wavelength region, where a strong $\beta_3$ is present, is a possible key reason behind the drop in output transmission, which could be seen in Figs. 3 and 4. The transmission window of the fiber in the long-wavelengths range extends to 1250 nm, so the SPM-induced spectrum broadening in the long-wavelengths region does not contribute to this output transmission loss.

As shown in the previous section the probable reason behind the transmission loss of the HC-ARF fiber is generation of an asymmetrical spectrum due to SPM and rotational Raman scattering outside the short-wavelength end of the fiber transmission window. In order to confirm this theory and find a solution to the problem of transmission loss, the gas atmosphere inside the fiber was changed to (a) nitrogen and (b) argon. For each gas, the output spectra for two input pulse durations were measured and compared (Figs. 11-12 and 13-14 respectively).

The propagation of 1.5 ps pulses in nitrogen-filled HC-ARF (Fig. 11) demonstrated broader spectra but much lower intensity than that in air (Fig. 6). At this range of input levels, compared to the SPM-induced blue shift of the main peak in air (Fig. 6), the nitrogen-related SRS started to have impact on the SPM-induced broadening of the spectrum and caused a red-shift of the pump pulse, although the spectrum is fairly weak. With argon, however, for the same input pulse a sharp spectral profile is maintained without distortion as the input peak power increases (Fig. 13); indeed the pulse width only slightly increased at the maximum input peak power of 22 MW due to SPM.

C. Gas filling

![Fig. 10. Width of the spectrum vs pulse duration at average power of 194 W (blue), 123W (orange) and 0.90W (green) in the 2.2m HC-ARF. The peak power ranges for those curves are 11-141 MW, 7-89 MW and 5-65 MW respectively.](image)

![Fig. 11. Output spectra for Nitrogen-filled 2.2 m HC-ARF (pulse duration 1.5 ps). The red line indicates the position of the original input laser wavelength of 1028 nm. The light green wavelength area covers the fundamental transmission band of the fiber.](image)

![Fig. 12. Output spectrum for Nitrogen-filled 2.2 m HC-ARF (pulse duration 230 fs). The inset replots the data on a different vertical scale to highlight the peaks in the long wavelength region. The blue line in the main graph shows the upper scale limit of intensity of the inset, and the red line indicates the position of the original input laser wavelength of 1028 nm. The light green wavelength area covers the fundamental transmission band of the fiber.](image)
and weaker SPM, the broadened spectrum in argon (Fig. 14) was less red-shifted than the spectrum in air and nitrogen (Figs. 9 and 12 respectively).

The effect of nonlinear broadening of the spectrum in the argon-filled fiber is weaker for a given pulse power. Firstly, argon has lower nonlinear refractive index \((2.9 \times 10^{-22} \text{m}^2/\text{W})\) than air \((12 \times 10^{-23} \text{m}^2/\text{W})\) or nitrogen \((7.5 \times 10^{-23} \text{m}^2/\text{W})\) [24], so the effect of SPM will be weaker. Secondly, argon is a monoatomic gas and thus does not have either vibrational or rotational modes [25-26]. This fact prevents the SRS effect from occurring, thus making argon a good choice for a gas for high-power pulse delivery.

In general, because the time for SPM to occur is reduced in the shorter fiber, all the measured spectra in the 3 different gases show reduced broadening. For the 1.5 ps pulse duration, the output spectra in air (Fig. 15(a)) and nitrogen (Fig.15(c)) each show a similar single peak with a slight distortion at the largest input peak power of 22 MW, while the spectra in argon (Fig. 15(e)) present a single peak with a symmetric and undistorted shape. For 230 fs pulses, in contrast to the strong spectral broadening in air (Fig. 15(b)); and nitrogen (Fig. 15(d)), the argon-filled fiber output spectra (Fig 15(f)) are broadened much less with only a few distinguishable peaks. In addition, as evident from Fig. 15(f), the spectral evolution in argon is very similar to the evolution of SPM-broadened spectra as described by Agrawal [18, pp. 102]. The only difference from a standard SPM-broadened spectrum is that the short-wavelength peak is stronger than the long-wavelength peak due to the strong third order dispersion on the blue side of the pump wavelength, which was discussed previously in Section 3.B. SRS does not occur at all in the argon-filled 65 cm piece of fiber.

From a practical perspective, filling the fiber with argon also enhances power transmission at higher peak powers. With the air-filled 2.2 m length, only 40% of the input pulse energy is transmitted with a pulse duration of 230 fs (Fig. 4), but this rises to 51% after argon filling (Fig. 16). The comparison of output peak power between air and argon is shown in Fig. 17. Although the curve of output power for argon (orange curve in Fig. 17) still shows a downward trend when the input peak power is increased above 122 MW, the maximum output peak power increases by about 14 MW.
Fig. 16. Transmission loss vs input pulse energy for various pulse durations in the 22 m HC-ARF with argon filled.

Fig. 17. Comparison of output peak power loss (polynomial fitting curve, 1% error) between air- and argon filling in a 2.2 m HC-ARF fiber across all investigated pulse durations (1.5 ps - 230 fs).

D. Vacuum system

Although filling the fiber with argon can reduce the nonlinear effects in HC-ARF to a certain extent, the spectra presented in Fig. 14 and Fig. 15(f) still develop strong asymmetric broadening for the input pulse duration of 230 fs. To further reduce nonlinearity to minimum, we built a vacuum system based on the previous setup in which any sort of gas in the fiber core is evacuated, thus eliminating as much as possible the effect of laser-molecule interactions.

Fig. 18. Setup for spectrum measurement in a vacuum system.

As shown in Fig. 20, when the maximum single pulse energy (33 μJ) and the shortest pulse length (230 fs) are used, at least 60% of the input power can be transmitted through the fiber, which is more than in the case of air- (40%) or argon filling (51%). The coupling efficiency of 60% at the maximum input peak power still shows a drop of transmission comparing to the original value of 82%. As a part of our measurement procedure we did not readjust the input coupling after evacuating the gas from the fiber. As a result, the most likely reason for that is the fact that the act of pumping the air out of the fiber physically moved it slightly in the holder. Another possible reason could be that the change of refractive index in the hollow core changed our coupling conditions and caused a small modal mismatch, which decreased the overall coupling efficiency. For the output/input peak power characteristics shown in Fig. 21, no transmission limit is observed in the vacuum-filled fiber as the input peak power increases up to the maximum of 141 MW, compared to the air- and argon filled fiber. Therefore, a larger transmittable peak power of 88 MW is provided, which is 26 MW and 12 MW higher than maximum transmitted peak power of air- and argon-filled fibers, respectively.

As shown in Fig. 19, for 1.5 ps input pulses, as shown in Fig. 19(a), the increasing input peak power only increases the intensity of the output spectra without changing their spectral shape. For pulses as short as 230 fs, as shown in Fig. 19(b), the single-peak spectrum starts to split into a double-peak when the input peak power is larger than 89 MW, which is a typical feature for an SPM-induced broadening. At the maximum input peak power of 141 MW the output spectrum (in blue) shows a broadened width of up to 41 nm, which is only 13% of the broadened spectral width in air and 25% of that in argon (Figs. 9 and 14 respectively). In addition, all the spectra presented in Fig. 19 measured in the vacuum environment are completely confined within the transmission band of the fiber, hence reducing the possibility of energy leak that causes transmission loss. Spectral broadening still remains in the vacuum filled fiber for 230 fs. The most probable reason behind this is the fact that we did not apply high vacuum to the fiber, rather only 20 mbar (measured inside the chamber), and the remaining gas molecules still participated in the nonlinear interactions, causing a loss in transmitted power for high peak-power pulses, based on the same mechanism as we described previously.

Fig. 19. Output spectra for the 2.2 m vacuum (20 mbar) HC-ARF: (a) 1.5 ps pulses; (b) 230 fs pulses. The light green wavelength area covers the fundamental transmission band of the fiber.
Detailed measurements are provided of the influence of input laser pulse conditions on the transmission of ultrashort pulses through HC-ARF, with the core filled with either air, nitrogen or argon. With an air-filled HC-ARF and an input peak power >30 MW a drop in transmission efficiency is observed. This transmission loss is caused by asymmetrical broadening of the pulse due to SPM and strong third-order dispersion of the fiber, which leads to generation of a strong blue-shifted peak outside of transmission window of the fiber. By comparing the spectra, we have shown that by instead filling the core with a neutral gas, such as argon, the onset of SPM broadening can be supressed, increasing the maximum transmission from 62 MW to 76 MW. By evacuating the fiber, the broadening of the spectrum is significantly supressed and limited to the fiber’s transmission band, which increases the maximum power transmitted to 88 MW and enhances fiber power-delivery capabilities. As no transmission limit of pulse propagation in the investigated vacuum HC-ARF is observed in our experiment, a larger transmission will be expected if stronger input pulses are given.

To further reduce the transmission loss of the fiber, one can redesign the fiber structure to shift the desired pump wavelength further away from the steep slope of GVD curve and suppress broadening of the spectrum beyond the short-wavelength end of the transmission window of the fiber.

Fig. 21. Comparison of output peak power loss (polynomial fitting curve, 1% error) between air- (blue) and argon (orange) filling, as well as vacuum (green) in a 2.2 m HC-ARF fiber across all investigated pulse durations (1.5 ps - 230 fs).

4. CONCLUSIONS

Detailed measurements are provided of the influence of input laser pulse conditions on the transmission of ultrashort pulses through HC-ARF, with the core filled with either air, nitrogen or argon. With an air-filled HC-ARF and an input peak power >30 MW a drop in transmission efficiency is observed. This transmission loss is caused by asymmetrical broadening of the pulse due to SPM and strong third-order dispersion of the fiber, which leads to generation of a strong blue-shifted peak outside of transmission window of the fiber. By comparing the spectra, we have shown that by instead filling the core with a neutral gas, such as argon, the onset of SPM broadening can be supressed, increasing the maximum transmission from 62 MW to 76 MW. By evacuating the fiber, the broadening of the spectrum is significantly supressed and limited to the fiber’s transmission band, which increases the maximum power transmitted to 88 MW and enhances fiber power-delivery capabilities. As no transmission limit of pulse propagation in the investigated vacuum HC-ARF is observed in our experiment, a larger transmission will be expected if stronger input pulses are given.

To further reduce the transmission loss of the fiber, one can redesign the fiber structure to shift the desired pump wavelength further away from the steep slope of GVD curve and suppress broadening of the spectrum beyond the short-wavelength end of the transmission window of the fiber.
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