Two-Octave Supercontinuum Generation of High-Order OAM Modes in Air-Core As$_2$S$_3$ Ring Fiber

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ABSTRACT In this work, we design and simulate an air-core As$_2$S$_3$ ring fiber for high-order orbital angular momentum (OAM) supercontinuum generation. We show that the chromatic dispersion of the ring fiber can be substantially tailored by proper optimization of the air-core radius. Two-octave supercontinuum carrying OAM$_{17,1}$ mode, spanning from 1560 to 6250 nm, is obtained by pumping a 50-fs 100-kW secant hyperbolic pulse centered at the wavelength of 3800 nm into the designed fiber with 50-µm air-core radius and 1-µm ring width. We further engineer the chromatic dispersion of some other OAM modes and perform simulations of supercontinuum spectra using different kilowatt-level peak power, which indicates that the fiber we design represents a promising avenue for supercontinuum generation of all the OAM)$_{1,l}$ modes ($|l| \leq 17$). The proposed fiber is suitable for the transmission of OAM beams in infrared wavelength range and it could promote the development and application of high-order OAM beams.

INDEX TERMS Supercontinuum generation, optical vortex, nonlinear optics, fiber.

I. INTRODUCTION

Orbital angular momentum (OAM) beams with the helical phase pattern have gained tremendous interest in recent years. In contrast to conventional linearly polarized (LP) modes, an OAM-carrying beam has a doughnut shaped intensity profile due to its twisted helical phase front. Besides, the amount of 2π phase shift that occurs in the azimuthal direction represent different states or modes, which are orthogonal to each other while propagating coaxially. These properties enabled researchers to push the frontiers of OAM in a variety of applications, such as optical communication systems [1]–[3], optical sensing [4], [5], micromanipulation [6], [7], laser material processing [8], [9]. Efficiently maintaining the OAM beams in the fiber is of great significance for these techniques. OAM beams are unable to propagate steadily in a conventional fiber as the quasi-degenerate modes can be easily coupled to each other. Ring fiber could potentially open the door to the OAM modes stable propagation as the OAM beams has a ring-shaped intensity profile as well [10].

An OAM beam has a limited wavelength range. Therefore, to expand its bandwidth satisfying various application requirements has become a laudable goal in research community. Supercontinuum (SC) generation of OAM beams spanning hundreds of nanometers wavelength range could potentially address this problem [11]. A recent study proposed the SC generation of OAM beam ($l = 1$) spanning from 696 to 1058nm at −20 dB using an annular core photonic crystal fiber (PCF) [12]. A SC generation carrying the high-order ($l = 8$) OAM beam was also experimentally demonstrated in the near-infrared spectrum based on air-core ring fiber [13]. In practical application, high-order OAM modes could be used to reach higher data transmission...
capacity though mode division multiplexing (MDM) in an all-fiber optical communication system. Besides, it could also be used in image coding and pattern recognition technology [14], quantum communication [15]–[17], high-precision sensing technology [18], to name a few. Unfortunately, no higher-order OAM mode SC has yet been theoretically studied or generated. One of the critical barriers is that higher-order OAM modes, which have more azimuthal phase periods in their transverse field distribution, feature faster variation and stronger dependence to the wavelength [19]. This makes it difficult to achieve flat and smooth chromatic dispersion for SC generation over wide wavelength range.

In this paper, we propose an air-core As$_2$S$_3$ ring fiber, which could support SC generation for high-order OAM modes up to $|l| = 17$. By carefully adjusting the air-core radius while maintaining 1-μm ring width, two-octave SC spanning from 1560 to 6250 nm can be generated for OAM$_{17,1}$ mode in the designed fiber. To the best of our knowledge, it is the highest-order OAM SC ever generated in optical fiber. The fiber design also shows the ability to engineer the chromatic dispersion for SC generation. Figure 2 illustrates that chromatic dispersion of OAM$_{15,1}$, OAM$_{11,1}$, OAM$_{11,1}$, and OAM$_{15,1}$ modes as examples. Meanwhile, all these SC spectra could cover two octaves at $-40$ dB level. Besides, the proposed fiber is suitable for the transmission of vector beams in 2000 - 6000 nm wavelength range and it could promote the development of high-order OAM beam applications in the mid-infrared waveband region.

### II. CONCEPT OF SC GENERATION AND FIBER STRUCTURE

First, Figure 1(a) displays the concept of the SC generation process carrying OAM beams using the designed air-core ring fiber, in which the spectrum is broadened due to the interaction of the nonlinear and dispersion effects. Different OAM modes can be supported, while the higher-order mode tends to require a larger air-core radii ($r_1$). Here, we propose to use a novel fiber design with cross section shown in Figure 1(b), which has a low-index air core, a high-index As$_2$S$_3$ ring, and a SiO$_2$ cladding. OAM modes can be better supported in this structure as the OAM beams also has a ring-shaped intensity profile. Chalcogenide glass (including S, Se, and Te) that we use as high-index layer of the designed fiber possesses ultrahigh nonlinear refractive index and exhibits wide transmission window in the infrared band. This property makes them promising for supercontinuum generation with flat profile and broad bandwidth [20], [21]. Besides, the diameter of the cladding of the designed fiber is 125 μm, the same as the standard single-mode optical fiber (SMF). The large material index contrast leads to sufficient effective refraction index difference between adjacent modes, which enables mode separation and preserves OAM modes purity across the supercontinuum range [22]. It is feasible to fabricate the designed fiber from the material selection and fiber structure perspectives [23], and fibers composed of silica and chalcogenide have been manufactured in practice [24].

### III. OAM$_{17,1}$ SUPERCONTINUUM GENERATION

Chromatic dispersion ($D$) is a decisively important parameter in the process of SC generation as it determines the velocities of different spectral components in a short pulse. The total dispersion in the designed fiber depends on both material and fiber structure contributions. Henceforth, we investigate the dependence of the chromatic dispersion on the geometrical parameters of the air-core ring fiber optimized for SC generation. During the simulation, we find near-zero dispersions could be achieved by adjusting the fiber air-core radii ($r_1$), while maintaining the 1-μm ring width ($\Delta r$). Our calculations indicate that a desirable region of low absolute dispersion occurs with a relatively large $r_1$. Moreover, $D$ increases monotonically with the mode order. Increasing the air-core radius makes $D$ lower, which represents a means of tailoring towards zero dispersion for different OAM modes with a certain order. Considering the 62.5-μm cladding radius, we optimize the air-core radius to 50 μm and find that the dispersion profile of OAM$_{15,1}$ - OAM$_{17,1}$ modes are close to zero over wide spectrum range.

The nonlinearity of the waveguide structure is another important factor in SC generation. Figure 2 illustrates that nonlinear coefficient ($γ$) and dispersion of the corresponding designed fiber operating from 1200 nm to 6800 nm wavelength range for the OAM$_{15,1}$ and OAM$_{17,1}$ modes. The nonlinear refractive index $n_2$ for As2S3 and SiO$_2$ is $3 \times 10^{-18}$ and $2.6 \times 10^{-20}$ m$^2$/W during the calculation respectively [25] and the material refractive indices of SiO$_2$ and As$_2$S$_3$ are obtained by using the Sellmeier equations in our model [26], [27].
Nonlinear coefficient and dispersion of (a) OAM modes and (b) OAM modes using the optimized designed fiber. 

Figure 2. Nonlinear coefficient and dispersion of (a) OAM$_{15,1}$ and (b) OAM$_{17,1}$ modes using the optimized designed fiber.

Figure 3. Intensity and phase distribution of OAM$_{15,1}$ and OAM$_{17,1}$ modes supported in the corresponding designed fiber. 

Figure 3 depicts the calculated intensity and phase distributions of OAM$_{15,1}$ and OAM$_{17,1}$ modes supported in the air-core ring fiber based on the optimized fiber structure with 50-µm $r_1$ and 1-µm $\Delta r$, which are obtained by analytical theory and validated by full-vector finite-element-method (FEM). The azimuthal phase variation of OAM$_{15,1}$ and OAM$_{17,1}$ are $30\pi$ and $34\pi$ corresponding to a topological charge number of 15 and 17, respectively.

The supercontinuum generation is numerically carried out by solving the generalized nonlinear Schrodinger equation (GNLSE), which considers the factors of both the linear effects (chromatic dispersion and loss) and the nonlinear effects (self-phase modulation, stimulated Raman scattering, and self-steepening effect) [23].

\[
\frac{\partial A}{\partial Z} + \frac{\alpha}{2} A - \sum_{n \geq 2} \frac{i^{n+1}}{n^1} \beta_n \frac{\partial^n A}{\partial T^n} = i\gamma (1-f_R) \left( |A|^2 A - \frac{i}{\omega_0} \frac{\partial}{\partial T} |A|^2 A \right) + i\gamma f_R \\
\times (1 + \frac{i}{\omega_0})(A \int_0^\infty R(\tau) |A(\tau, T-\tau)|^2 \partial \tau) 
\] 

where $\alpha$, $\omega_0$, $\tau$, and $f_R$ means the loss coefficient, input pulse frequency, present time frame, fractional contribution due to delayed Raman function $R(\tau)$, respectively, [28]. $\beta_n$ means the $n$th-order dispersion and up to the 12-th order of dispersion is taken into consideration for this simulation. Besides, we used a full-vector model to obtain the Kerr nonlinear coefficient $\gamma$ in the simulation [29]. In the simulation, we set the fiber loss as 1 dB/m from 1 µm to 6 µm, and it gradually increases to 10 dB/m at wavelength larger than 6 µm, according to the As$_2$S$_3$ material loss [25] and the previous experiment result of As$_2$S$_3$ ring fiber [30].

Figure 4(a) presents the SC generation of OAM$_{15,1}$ using the 100-kW after the 0, 0.5, 1, 2, 4 and 6-mm propagation lengths in the designed fiber, respectively. The previous experiment demonstrates that the SC generates in small-core nonlinear fibers using comparable kW-level pulses in the past [31], which shows the incident peak power ($P_0$) is feasible. Moreover, simulations of OAM modes SC generation are performed using a hyperbolic secant pulse of full-width at half maximum ($\tau_{FWHM}$) = 50 fs duration and input pulse centered at $\lambda = 3800$ nm wavelength. We choose the pumped wavelength at 3800 nm, which fits within the broad emission band (3000 - 5000 nm) of future praseodymium (Pr$^{3+}$)-doped chalcogenide fiber lasers [32], [33]. The result shows that the broadening of the output pulse can be obtained in only a few millimeters propagation length, which is mainly due to the strong nonlinearity and low dispersion. Finally, the simulated SC spectral range covers 4825 nm from 1600 to 6425 nm at -40 dB level after 6-mm propagation length.

Similarly, Figure 4(b) shows the spectrum for the OAM$_{17,1}$ mode along the As$_2$S$_3$ air-core ring fiber as a function of different length. After 6-mm distance, a 4690 nm SC spectrum carrying vortex beam is formed from 1560 to 6250 nm at -40 dB level, which covers two-octave bandwidth.

Figure 5(a) and (c) show the temporal evolution of the input pulse with OAM$_{15,1}$ and OAM$_{17,1}$ modes in the designed fiber, while Figure 5(b) and (d) illustrate their corresponding spectral evolution. First, we note that the initial stage of propagation is dominated by approximately...
symmetrical spectral broadening, which occurs within the first 0.5 mm due to self-phase modulation (SPM). After that, new spectrum components are generated due to optical wave breaking (OWB), which can also be explained as a degenerate four-wave mixing (FWM) process. Although the majority of spectral broadening occurs within the initial stage, an obvious redshift of long wavelengths continues, while the short-wavelength components of the SC does not extend further after 2-mm propagation [34], [35].

IV. FIBER PARAMETER OPTIMIZATION FOR LOW-ORDER OAM SUPERCONTINUUM GENERATION

From the above studies of SC generation in 50-µm air-core radius and 1-µm ring width designed fiber, we note that smooth and flat SC of OAM\textsubscript{17,1} and OAM\textsubscript{15,1} mode can be realized. In this Section, we characterize some other OAM modes (|l| \leq 17) SC generation by optimizing the fiber structure to further show the ability to engineer the chromatic dispersion.

Figure 6(a) indicates that by increasing the \( r_1 \) of designed fiber from 4 to 8 µm, the dispersion of OAM\textsubscript{2,1} mode become lower and flatter. Similarly, based on the analysis, low dispersion curves of some other OAM modes are also effectively achievable using larger \( r_1 \), which demonstrate the ability to engineer the chromatic dispersion of OAM modes in the designed air-core ring fiber through the precise tuning of its air-core radius. In particular, one can observe in Figure 6(d) that the dispersion curve changes slower as the \( r_1 \) has become large to certain extend.

We select some optimized dispersions of the designed fiber for SC generation carrying high-order OAM modes. The air-core radii of these optimized fiber designs with fixed 1-µm ring width are 8, 15, 24, 40 µm, which are used to generate OAM\textsubscript{2,1}, OAM\textsubscript{4,1}, OAM\textsubscript{7,1}, and OAM\textsubscript{11,1} supercontinua, respectively. The corresponding dispersion curves (red curves) are shown in Figure 6. As a result, we obtain flattened dispersion of OAM\textsubscript{2,1} with \( < \pm 30 \) ps/nm/km variation over a 3240-nm optical bandwidth ranging from 2150 to 5390 nm as shown in Figure 6(a). The low dispersion of OAM\textsubscript{4,1} is plotted in Figure 6(b), with a total dispersion variation of \( < \pm 30 \) ps/nm/km over a 3300-nm bandwidth from 2130 nm to 5430 nm. Figure 6(c) and (d) show \( < \pm 30 \) ps/nm/km dispersion curves for OAM\textsubscript{7,1} and OAM\textsubscript{11,1} modes, spanning 3295 nm and 3355 nm wavelength range, respectively.
FIGURE 6. Chromatic dispersion curves of (a) OAM_{2,1}, (b) OAM_{4,1}, (c) OAM_{7,1} and (d) OAM_{11,1} modes with different fiber air-core radii (r_1).

Figure 7 shows the intensity and phase distributions of OAM_{2,1}, OAM_{4,1}, OAM_{7,1}, and OAM_{11,1} modes supported in the air-core ring fiber based on different optimized structures through the coherent superposition of the even and odd vector modes with \( \pi/2 \) phase shift: OAM_{l,1} = HE_{l+1,1}^{even} + i \times HE_{l+1,1}^{odd}, |l| = 3, 5, 8, 12. These results are calculated through full-vector finite-element method (FEM). The left color bar represents the intensity level of the normalized field strength of the OAM modes, while the right color bar stands for the phase change of the OAM modes. One can observe in Figure 7 that the intensity distributions of OAM modes still remain annular shape and the OAM_{7,1} mode shows a 2\( \pi \) phase change azimuthally. Moreover, it is noted that the intensity distributions of the modes are well-confined within the As_{2}S_{3} ring of the fiber.

FIGURE 7. Intensity and phase distribution of the OAM_{2,1}, OAM_{4,1}, OAM_{7,1} and OAM_{11,1} modes supported in the corresponding designed fiber.

FIGURE 8. Nonlinear coefficient of OAM_{2,1}, OAM_{4,1}, OAM_{7,1} and OAM_{11,1} modes in the designed fiber with 8, 15, 24, 40-\( \mu \)m air-core radii (r_1), respectively.

Figure 8 illustrates that nonlinear coefficient (\( \gamma \)) of the corresponding designed fibers operating from 1200 nm to 6800...
nm wavelength range for the OAM\(_{2,1}\), OAM\(_{4,1}\), OAM\(_{7,1}\), and OAM\(_{11,1}\) modes. \(\gamma\) increases with the smaller \(r_1\), which is mainly due to the effective mode areas (\(A_{\text{eff}}\)) of the corresponding OAM mode varies significantly when the size of As\(_2\)S\(_3\) ring varies, and \(\gamma\) is inversely proportional to the effective mode area of the specific mode.

The evolution of SC generation is investigated when the pump optical mode is changed from OAM\(_{2,1}\) to higher-order OAM modes. A 50-fs hyperbolic secant pulse train centered at \(\lambda = 3800\) nm is incident into the designed fibers, where these optimized fibers (\(r_1 = 8, 15, 24, 40\) \(\mu\)m) are all pumped in the normal dispersion regime (\(D = -14.94, -20.27, -19.86\) and \(-24.32\) ps/(km-nm), respectively). The calculated output spectra after 6-mm propagation in different fiber designs are shown in the Figure 9, when the pulse with different peak power is input.

Increasing the input pulse power leads to a broader SC bandwidth and higher-order OAM mode needs a larger input pulse power. This is mainly because the designed fiber for higher-order OAM modes has a larger air-core radius, resulting in a smaller nonlinear coefficient. Consequently, a pump pulse with larger peak power should be used for higher-order mode to stimulate an equivalently broad spectrum compared to low-order mode. Figure 9(a) shows the corresponding spectral profile simulated for the designed fiber with 8-\(\mu\)m air-core radius to support OAM\(_{2,1}\) mode where we observe that an output spectrum spanning from 1357 to 6295 nm at \(-40\) dB from the top is obtained for an input pulse with 30 kW peak power. Similarly, SC of OAM\(_{4,1}\) mode displays a spectral broadening spanning from 1550 to 6415 nm at \(P_0 = 50\) kW in Figure 9(b). In Figure 9(c), the simulated SC spectral range for the OAM\(_{7,1}\) mode covers 4930 nm from 1360 to 6290 nm with 70-kW input power. For the OAM\(_{11,1}\), the simulated SC spectral range covers 4940 nm from 1590 to 6530 nm with 100-kW \(P_0\) as shown in Figure 9(d).

**TABLE 1.** High-order OAM SC generation in designed fibers.

<table>
<thead>
<tr>
<th>Fiber Structure</th>
<th>Supported OAM modes</th>
<th>SC Bandwidth (-40dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r_1 = 8) (\mu)m, (\Delta r = 1) (\mu)m</td>
<td>OAM(_{2,1})</td>
<td>1357 to 6295 nm</td>
</tr>
<tr>
<td>(r_1 = 15) (\mu)m, (\Delta r = 1) (\mu)m</td>
<td>OAM(_{4,1})</td>
<td>1550 to 6415 nm</td>
</tr>
<tr>
<td>(r_1 = 24) (\mu)m, (\Delta r = 1) (\mu)m</td>
<td>OAM(_{7,1})</td>
<td>1360 to 6290 nm</td>
</tr>
<tr>
<td>(r_1 = 50) (\mu)m, (\Delta r = 1) (\mu)m</td>
<td>OAM(_{11,1})</td>
<td>1590 to 6530 nm</td>
</tr>
<tr>
<td>(r_1 = 50) (\mu)m, (\Delta r = 1) (\mu)m</td>
<td>OAM(_{17,1})</td>
<td>1560 to 6250 nm</td>
</tr>
</tbody>
</table>

**TABLE 2.** OAM-SC generations in fibers.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>OAM mode order</th>
<th>SC Range</th>
<th>Bandwidth</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>As(_2)S(_3) ring PCF</td>
<td>(</td>
<td>l</td>
<td>= 1)</td>
<td>1196-2418 nm (-20 dB)</td>
</tr>
<tr>
<td>SiO(_2) annular-core PCF</td>
<td>(</td>
<td>l</td>
<td>= 1)</td>
<td>696-1058 nm (-20 dB)</td>
</tr>
<tr>
<td>Schott glass slotted ring fiber</td>
<td>(</td>
<td>l</td>
<td>= 3)</td>
<td>950-1850 nm (-20 dB)</td>
</tr>
<tr>
<td>air-core SiO(_2) ring fiber</td>
<td>(</td>
<td>l</td>
<td>= 8)</td>
<td>630-1430 nm (-20 dB)</td>
</tr>
<tr>
<td>air-core As(_2)S(_3) ring fiber</td>
<td>(</td>
<td>l</td>
<td>= 17)</td>
<td>2850-6573 nm (-20 dB)</td>
</tr>
<tr>
<td>air-core As(_2)S(_3) ring fiber</td>
<td>(</td>
<td>l</td>
<td>= 17)</td>
<td>1560-6250 nm (-40 dB)</td>
</tr>
</tbody>
</table>

Finally, we conclude the SC generation of different order OAM beams in our designed fiber as displayed in TABLE 1. From the table, we can obviously observe the relationship between fiber air-core radius and OAM order. With proper As\(_2\)S\(_3\) air-core ring fiber structure design, the broadband supercontinuum could be potentially achieved for other OAM modes (\(|l| \leq 17\)). We further compare our work with the previous work for OAM-SC generation as shown in TABLE 2. To the best of our knowledge, this work achieves the highest order of OAM SC ever generated in an optical fiber.
V. CONCLUSION
In summary, the 6-mm designed air-core As$_2$S$_3$ ring fiber is proposed for high-order OAM supercontinuum generation. The characteristics of the optical field distribution, chromatic dispersion and nonlinear coefficient are analyzed numerically for different OAM beams (OAM$_{2}$, OAM$_{3}$, OAM$_{7}$). OAM$_{11}$, OAM$_{15}$, and OAM$_{17}$) in the designed fiber with different air-core radii. Generating SC of higher-order OAM needs a larger air-core radius of the designed fiber and a higher input peak power according to our simulations. Moreover, we calculated two-octave SC spectra of light-carrying OAM$_{1}$ mode ($l = 2, 4, 7, 11, 15, 17$) with a 50-fs secant hyperbolic pump pulse centered at 3800 nm in the mid-infrared region. The new type air-core As$_2$S$_3$ ring fiber we designed could be a good candidate for generating supercontinuum carrying OAM modes, which is applicable for various nonlinear applications.

REFERENCES

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