Original Research Paper

Volume - 13 | Issue - 01 | January - 2023 | PRINT ISSN No. 2249 - 555X | DOI : 10.36106/ijar

Physics

ON-CHIP PLANER WAVEGUIDES FOR SUPERCONTINUUM GENERATION IN THE MID-IR REGION OF ELECTROMAGNETIC SPECTRUM: A REVIEW

Megha Mangal	Research scholar, Department of Physics, University of Rajasthan, Jaipur-302004, India
Bharat Lal Meena	Assistant Professor, Department of Physics, University of Rajasthan, Jaipur-302004, India
Kanchan Gehlot*	Assistant Professor, Department of Physics, University of Rajasthan, Jaipur-302004, India*Corresponding Author

ABSTRACT On-chip planer optical waveguide-based sources for supercontinuum (SC) generation have become highly attractive devices in the twenty-first century. Mid-IR SC sources in the 2-20 µm wavelength region are advantageously used for gas sensing, high-sensitivity molecular detection, security, and industrial applications. These integrated photonic devices are cost-effective, scalable, and robust, and also offer more flexibility in tailoring the dispersion characteristics relative to other SC generation techniques. This article reviews the evolution of SC sources from fiber-based devices to optical waveguide-based devices and presents a historical as well as recent progress in various types of on-chip optical waveguides with physical mechanisms involved in generating coherent SC sources.

KEYWORDS : On-chip waveguides, Supercontinuum generation, integrated photonic devices

INTRODUCTION

The interaction of short and high intensity optical pulses to nonlinear media allows the generation of a broad continuum of frequencies called supercontinuum (SC) [1,2]. The presence of distinctive absorption bands of the majority of biomolecules in the mid-infrared (mid-IR) region has generated a lot of interest in mid-IR SC sources over the last couple of decades [3]. SC are highly coherent, intense, broadband, and compact light sources [4]. The mid-IR SC sources find application in flow cytometry, metrology, remote sensing, chemical sensing, optical coherence tomography, telecommunications, nonlinear mid-IR spectroscopy, particle analysis, and infrared imaging [5-10]. The basic nonlinear processes that cause spectral broadening of a short input pump beam are self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman scattering (SRS), four-wave mixing (FWM), soliton dynamics, and modulation stability [11-14]. The journey of supercontinuum sources started in the 1960s together with further investigation in this field. Supercontinuum was first reported in bulk media in 1970 but there were a number of drawbacks to SC generation in bulk media, including low and unstable output intensities, limited spectral broadening, dispersion, and diffraction, which involved a complex coupling between temporal and spatial effects, as well as the requirement for high input power, which could cause harm to the material [15-16]. For efficient SC generation, optical fibers attracted a widespread interest of researchers, as the optical fibers provide confine and guide light in the narrow core of the fiber providing the high intensity of the optical power thus leading to enhanced nonlinear interaction. The first report of a broadband spectrum of bandwidth of the order of 200 THz in an optical fiber by launching an input optical pulse with peak power of the order of a few kW and a zero-dispersion wavelength (ZDW) around 1.3 µm [10]. The combined cascade of SRS and SPM dominated the broadening of the spectrum in the visible region of the electromagnetic spectrum. Although conventional optical fibers have better guidance properties than bulk media, photonic crystal fibers (PCFs) designed by microstructured holes in the optical fiber provide an additional degree of freedom to optimize the structure by controlling the number of holes, size, and their periodicity [17]. An extensive review of SC generation in PCF was reported by Dudley et.al in 2006 [18]. Dudley and Taylor also published a book that comprehensively studies the SC generation mechanism in fibers [2]. Although a high nonlinearity and desired dispersion characteristics can be obtained in a PCF, another way of improving the dispersion characteristics, and nonlinearity was reported by an appropriate tapering of optical fiber [19]. Therefore, PCFs provide a promising platform for the design and development of high-brightness, spatially coherent mid-IR supercontinuum light sources in soft glasses [20]. The ever-growing demand for miniaturization of the SC sources and to achieve compatibility with integrated circuits in on-chip applications, a lot of research focus has switched from fiber-based devices to devices based on planar optical waveguides. In high-index contrast planar optical waveguides, the effective mode area of the propagating mode is much smaller compared to the optical fibers and PCFs which enhances the nonlinearity providing better opportunities in integrated photonic devices [21]. Supercontinuum generation has been described in a variety of planar optical waveguides, including the strip, rib, ridge, and slot waveguides, using a variety of materials, including silica, silicon, silicon nitride, fluoride, tellurite, aluminium gallium arsenic (AlGaAs), GaAsSe, and chalcogenide [21-29]. In this paper, we review the progress of research on the on-chip optical waveguides for the generation of the mid-IR supercontinuum, and the evolution of broadband spectra in a variety of on-chip planer waveguides and the underlying physical mechanisms that affect the supercontinuum generation.

SUPERCONTINUUM GENERATION IN ON-CHIP PLANER OPTICAL WAVEGUIDES

On-chip planer optical waveguide-based sources have become highly attractive devices for researchers in the field of supercontinuum generation in the twenty-first century [21-29]. Integrated photonic devices are cost-effective, scalable, and robust, and also offer more flexibility in tailoring the dispersion characteristics relative to optical fibers. The first demonstration of SC in an on-chip silicon rib waveguide was reported by launching a chirped gaussian pulse of peak power 20 GW/cm^2 centered at the wavelength of 1550 nm [30]. Five times spectral broadening of the input pulse was reported which was in good agreement with the theoretical model based on two-photon absorption (TPA) and SPM [30]. Although these findings provide the first step toward SC generation in an integrated on-chip planer waveguide, the Si-rib waveguide used in this paper has lower optical confinement than Si-nanowire waveguides. The high index contrast between Si-core embedded in silica or air-cladding materials provides stronger optical confinement that affects the third-order nonlinearity such as SPM, and TPA, which are crucial for spectral broadening. A nonlinear phase shift of 1.5-π is achieved by pumping an input pulse at a power of 12 W in a 4 mm long Si-nanowire waveguide [31]. Most of the previously reported supercontinua were generated either by higher-order soliton fission in anomalous dispersion regime or by self-phase modulation in normal dispersion regime in waveguides and fibers. In contrast to this, a 10 mm long Ta_2O_5 planer waveguide generated broad spectra spanning up to ~600 nm by launching a high peak power pulse in a normal dispersion region far from the zero-dispersion wavelength (ZDW) [32]. Similarly, in a normal dispersion regime, Psaila et. al experimentally resulted in 600 nm broad spectra from 1320 to 1920 nm. In the smaller wavelength range in the normal dispersion regime, SPM and XPM are the main factors that broaden the spectra. Whereas, SRS is the major contributory nonlinear process that causes spectral broadening in a multimode waveguide having a smaller effective mode area [33]. Earlier, picosecond pulses were used to generate supercontinuum in planar optical waveguides, which soon got substituted by femtosecond pulses after the observation of SC extended over 400 nm achieved by launching a femtosecond input pulse in a silicon-on-insulator-based waveguide [34]. The broadband

SC generation was obtained by optimizing the optical waveguide structures to lie in the anomalous dispersion region and with its ZDW near to 1500 nm. Soliton fission, SPM, and generation of Cherenkov Radiation cause the spectral broadening from 1.3 to 1.7 µm. This study clarifies that ultrashort pulses of duration in femtosecond and short on-chip optical waveguides (<1 cm) are sufficient to create a supercontinuum that covers the whole visible spectrum region [34].

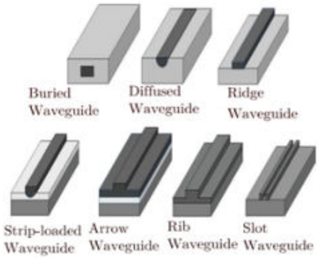

Figure 1. Schematic diagram of different types of on-chip optical waveguides.

The researchers generated the SC in the wavelength range of 3.0-8.5 µm, 0.7-5.2 µm, and 1.76-14.42 µm, respectively, by using on-chip planner ridge waveguides made of silicon germanium, arsenic pentasulfide (As2S5), and arsenic triselenide (As2Se3), respectively [35-37]. It is observed that material plays an important role in the nonlinearity of the waveguide structure. To generate SC in the mid-IR region chalcogenide material exhibits higher optical Kerr nonlinearities, high refractive indices, and wide transparency window compared to silica covering near-infrared and mid-infrared regions of the spectrum [38]. Due to suitable optical properties for SC, chalcogenide has been widely used to design a variety of optical planer waveguides as shown in Fig.1 to achieve mid-infrared SC sources. Several research groups have generated the SC using different waveguide structures formed using chalcogenide materials with optimized parameters such as input power (P0), pump wavelength, (λ0) pulse duration (T0), and length of the waveguide (Z), as shown in Table 1.

TABLE – 1 SC IN VARIETY OF ON-CHIP WAVEGUIDES

Ref	Structure (material)	P0(W) λ0(µm)	Z(mm) T0 (fs)	SC (µm)
[45]	RW (SiGe)	8 mW 8.5 µm	5.5 mm 220 fs	3-13
[36]	RDW (As2S5)	25 kW 2.5 µm	5 mm 100 fs	0.7-5.2
[37]	RDW (As2Se3)	900 W 3.3 µm	0.87 mm 100 fs	1.76-14.42
[38]	CW (As2S3)	68 W 1.55 µm	60 mm 610 fs	1.25-2
[47]	RW (GaSbS)	6.4 kW 2.8 µm	5 mm 497 fs	1-9.7
[48]	RW (GeAsS)	4.5 kW 4.18 µm	18 mm 330 fs	2-10
[49]	RW (As2Se3)	2.5 kW 2.8 µm	2.5 mm 200 fs	1.2-7.2
[44]	nanowire (GeAsSe)	25 W 1.55 µm	18 mm 50 fs	1.2-2.5

CW= channel waveguide, RW=rib waveguide, RDW=ridge waveguide.

In most of the optical waveguides, FWM dominates spectral broadening as its phase-matching condition of having ZDW at the pump wavelength is satisfied. FWM generates sidebands to both sides of the pulse spectrum for the shorter propagation lengths while the soliton fission dominates SC for further distances larger than 2 cm [38]. A 750 nm wide SC spectra ranging from 1.2-2 µm was observed through a 6 cm long As2S3 planer waveguide experimentally, which resulted from the contribution of both FWM and soliton fission. It was observed that SRS provides additional broadening of the SC towards the higher wavelength end of the spectrum [38]. Dispersion tailoring is the most essential characteristic of SC in optical waveguides for providing a phase-matching condition for the FWM. The novel optical waveguides, such as the slot waveguide, offers more advantage as the dispersion profile can be tailored desirably by optimizing the waveguide structure parameters [39-40]. The chromatic dispersion of the horizontal silicon slot waveguide has been theoretically investigated and optimized to obtain a low and nearly flat dispersion profile over a wide range of wavelengths with four ZDWs [41]. A low and flat dispersion varying between −22 and + 20 ps/(nm·km) over a 667-nm bandwidth, generating supercontinuum generation in the near infra-red region from 1435 to 2102 nm was reported. The optical waveguides that have multiple ZDWs provide multiple choices of wavelengths at which the input pulse can be launched [41]. The higher-order dispersion also influences the spectral broadening of the SC spectrum in a planar optical waveguide [42]. Karim et. al theoretically tailored the dispersion of the As2Se3 suspended core channel waveguide and experimentally pumped the input pulse at different wavelengths around 1.55 µm, 2.8 µm, and 3.5 µm near the different ZDWs in the anomalous regime [43]. In another work, the structure parameters of the GeAsSe channel waveguide were numerically optimized for achieving low and nearly flat dispersion over a broad range of wavelengths with multiple ZDWs and also reported a 1300 nm wide spectrum [44].

The sensing of chloroform by suing the optical absorption wavelength of chloroform solutions at 1695 nm was carried out by designing an on-chip SC light source from a 21 mm long on-chip planer GeSbSe waveguide [6]. The waveguide exhibited a broad spectrum ranging from 1380 to 2050 nm by pumping a 800 fs input pulse at the wavelength of 1.56 µm with the peak power of 0.8 kW. This study is a significant step toward developing photonic chip-based supercontinuum sources for sensing applications [6]. The choice of pump duration plays a critical role in the broadening and coherence characteristic of the supercontinuum generation. To obtain highly coherent SC, ultrashort pulses shorter than 100 fs are required. The self-similar pulse compression scheme provides a higher compression factor in the nonlinear optical waveguides. A tapered suspended silicon strip waveguide had been investigated to generate SC using such a compressed pulse [23]. In this work, it was reported that the tapering of a waveguide exponentially decreases the group velocity dispersion profile along the direction of propagation that was used to obtain a compressed pulse of duration 47.06-fs with a peak power of 27.63 W by launching a 1-ps pulse of peak power 1.67 W centered at the 2.8 µm wavelength. The compressed pulse and the original pulse were launched separately in the suspended strip waveguide to analyze the difference in the generated broad Sc spectrum is compared. When an uncompressed pulse of duration 1 ps is launched, the modulation instability leads the SC generation and exhibited a spectrum spanning from 2.43 to 3.13 µm. Whereas the soliton fission dominates the SC generation when a 47.06 fs pulse is launched, providing a smoother and highly coherent SC extending from 2.13 to 4.03 µm [23].

A very broad and highly coherent spectrum extending over the wavelength range of 3 to 13 µm was reported experimentally by 45. Montesinos et. al by launching a 220 fs wide input pulse of peak power 8 mW at the wavelength of 8.5 µm through 5.5 mm long graded-index SiGe waveguides [45]. In this work, the supercontinuum generation was studied by pumping the input pulses at different wavelengths of 7.5 µm, 8.5 µm, and 9.4 µm and different input powers of 6.5 W and 2.6 kW.

In a recent study, it has been reported that the photonics-integrated devices coated with 2D graphene oxide films enhance the third-order nonlinear performance, particularly the contribution of SPM in the SC generation in on-chip planer waveguides [46]. In another recent work reported in 2022, an integrated silicon nitride waveguide coated with a graphene oxide layer has been shown to produce nearly 2.4 times broader spectra compared to the uncoated integrated devices [26]. This has driven the researchers to coat the integrated devices with suitable materials to provide an enhancement in the broadening of the SC generation in the mid-IR region of the electromagnetic spectrum [26].

CONCLUSION

In the past couple of decades, the generation of SC in the planar optical waveguides has attracted a lot of research attention in order to miniaturize the supercontinuum sources for on-chip applications. Apart from the low footprint of the planar optical waveguides, their tailorable dispersion characteristics have offered to achieve desirable dispersion profiles and the multiple ZDWs. By using a variety of optical waveguide designs, such as strip, rib, ridge, and slot waveguides, and nonlinear materials, silica, silicon, silicon nitride, fluoride, tellurite, AlGaAs, GaAsSe, and chalcogenides, SC generation has been achieved in the visible, near-infrared, and mid-infrared ranges of the electromagnetic spectrum. A very broad and highly coherent SC generation spanning from 3-13 μm in an on-chip waveguide has been achieved experimentally. The broadband SC sources in the mid-IR have opened a potential use of SC sources in sensing and biomedical applications. The nonlinear response of the planar optical waveguides has been shown to improve with the use of materials such as Graphene Oxide, which provides further directions for improving the on-chip SC sources.

REFERENCES:

1. Morris, James M., et al. "Ge22As20Se58 glass ultrafast laser inscribed waveguides for mid-IR integrated optics." Optical Materials Express 8.4 (2018): 1001-1011.
2. Dudley, J. M., & Taylor, J. R. (Eds.). (2010). Supercontinuum generation in optical fibers. Cambridge University Press.
3. Labruyère, A., Tonello, A., Couderc, V., Huss, G. and Leproux, P., (2012), "Compact supercontinuum sources and their biomedical applications." Optical Fiber Technology, 18(5), pp.375-378
4. Moselund, P. M., Petersen, C., Dupont, S., Agger, C., Bang, O., & Keiding, S. R. (2012, May). "Supercontinuum: broad as a lamp, bright as a laser, now in the mid-infrared." In Laser Technology for Defense and Security VIII (Vol. 8381, pp. 265-270). SPIE.
5. Udem, T., Holzwarth, R., & Hänsch, T. W. (2002). "Optical frequency metrology." Nature, 416(6877), 233-237.
6. Du, Q., Luo, Z., Zhong, H., Zhang, Y., Huang, Y., Du, T., ... & Hu, J. (2018). "Chip-scale broadband spectroscopic chemical sensing using an integrated supercontinuum source in a chalcogenide glass waveguide." Photonics Research, 6(6), 506-510.
7. Ghanbari, A., Kashaninia, A., Sadr, A., & Saghaei, H. (2017). "Supercontinuum generation for optical coherence tomography using magnesium fluoride photonic crystal fiber." Optik, 140, 545-554.
8. Smirnov, S. V., Ania-Castañón, J. D., Kobtsev, S., & Turitsyn, S. K. (2016). "Supercontinuum in telecom applications." In The Supercontinuum Laser Source (pp. 371-403). Springer, New York, NY.
9. Kano, H., & Hamaguchi, H. O. (2003). "Characterization of a supercontinuum generated from a photonic crystal fiber and its application to coherent Raman spectroscopy." Optics letters, 28(23), 2360-2362.
10. Lin, C., & Stolen, R. H. (1976). "New nanosecond continuum for excited state spectroscopy." Applied Physics Letters, 28(4), 216-218.
11. Husakou, A. V., & Herrmann, J. (2001). "Supercontinuum generation of higher-order solitons by fission in photonic crystal fibers." Physical Review Letters, 87(20), 203901.
12. Baldeck, P., & Alfano, R. (1987). "Intensity effects on the stimulated four photon spectra generated by picosecond pulses in optical fibers." Journal of lightwave technology, 5(12), 1712-1715.
13. Agrawal, G. P. "Nonlinear Fiber Optics," 6th ed., (Elsevier Academic Press, Oxford, 2019).
14. Boyd, R. W. (2020). "Nonlinear optics. Academic press."
15. Alfano, R. R., & Shapiro, S. L. (1970). "Emission in the region 4000 to 7000 Å via four-photon coupling in glass." Physical Review Letters, 24(11), 584.
16. Manassah, J. T., P. P. Ho, A. Katz, and R. R. Alfano, 1984, "Ultrafast supercontinuum laser source," Photonics Spectra 18, 53–59.
17. Ranka, J. K., Windeler, R. S., & Stentz, A. J. (2000). "Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm." Optics letters, 25(1), 25-27.
18. Dudley, J. M., Genty, G., & Coen, S. (2006). Supercontinuum generation in photonic crystal fiber. Reviews of modern physics, 78(4), 1135.
19. Birks, T. A., Wadsworth, W. J., & Russell, P. S. J. (2000). "Supercontinuum generation in tapered fibers." Optics letters, 25(19), 1415-1417.
20. Chang, G., Norris, T. B., & Winful, H. G. (2003). "Optimization of supercontinuum generation in photonic crystal fibers for pulse compression." Optics letters, 28(7), 546-548.
21. Møller, U., Yu, Y., Petersen, C.R., Kubat, I., Brilland, L., Méchin, D., Troles, J., Luther-Davies, B. and Bang, O., (2014), July. "High average power mid-infrared supercontinuum generation in a suspended core chalcogenide fiber." In Specialty Optical Fibers, Optica Publishing Group, (pp. JM5A-54).
22. Sylvestre, T., Genier, E., Ghosh, A. N., Bowen, P., Genty, G., Troles, J., ... & Dudley, J. M. (2021). "Recent advances in supercontinuum generation in specialty optical fibers." JOSA B, 38(12), F90-F103.
23. Cheng, Y., Yuan, J., Mei, C., Li, F., Kang, Z., Yan, B., ... & Farrell, G. (2020). "Self-similar picosecond pulse compression for supercontinuum generation at mid-infrared wavelength in silicon strip waveguides." Optics Communications, 454, 124380.
24. Oh, D. Y., Sell, D., Lee, H., Yang, K. Y., Diddams, S. A., & Vahala, K. J. (2014). "Supercontinuum generation in an on-chip silica waveguide." Optics letters, 39(4), 1046-1048.
25. Kou, R., Hatakeyama, T., Horng, J., Kang, J. H., Wang, Y., Zhang, X., & Wang, F. (2018). "Mid-IR broadband supercontinuum generation from a suspended silicon waveguide." Optics Letters, 43(6), 1387-1390.
26. Moss, D. (2022). "Supercontinuum generation in 2D graphene oxide film coated SiN waveguides."
27. Liu, L., Qin, G., Tian, Q., Zhao, D., & Qin, W. (2011). "Numerical investigation of mid-infrared supercontinuum generation up to 5 μm in single mode fluoride fiber." Optics Express, 19(11), 10041-10048.
28. Liao, M., Gao, W., Duan, Z., Yan, X., Suzuki, T., & Ohishi, Y. (2012). "Supercontinuum generation in short tellurite microstructured fibers pumped by a quasi-cw laser." Optics Letters, 37(11), 2127-2129.
29. Kiroriwal, M., & Singal, P. (2021). "Numerical analysis on the supercontinuum generation through Al0." 24Ga0. 76As based photonic crystal fiber. Sādhanā, 46(3), 1-8.
30. Boyraz, O., Indukuri, T., & Jalali, B. (2004). "Self-phase-modulation induced spectral broadening in silicon waveguides." Optics Express, 12(5), 829-834.
31. Yamada, H., Shirane, M., Chu, T., Yokoyama, H., Ishida, S., & Arakawa, Y. (2005). "Nonlinear-optic silicon-nanowire waveguides." Japanese journal of applied physics, 44(9R), 6541.
32. Netti, M. C., Perney, N. M. B., Baumberg, J. J., Charlton, M. D. B., Cox, S. J., Hassan, M. A., ... & Drexler, W. (2004, February). "White light continuum generation in planar waveguides." In Advanced Solid-State Photonics (p. PDP3). Optical Society of America.
33. Psaila, N. D., Thomson, R. R., Bookey, H. T., Shen, S., Chiodo, N., Osellame, R., ... & Kar, A. K. (2007). "Supercontinuum generation in an ultrafast laser inscribed chalcogenide glass waveguide." Optics Express, 15(24), 15776-15781.
34. Yin, L., Lin, Q., & Agrawal, G. P. (2007). Soliton fission and supercontinuum generation in silicon waveguides. Optics letters, 32(4), 391-393.
35. Sinobad, M., Monat, C., Luther-Davies, B., Ma, P., Madden, S., Moss, D. J., ... & Grillet, C. (2018). Mid-infrared octave spanning supercontinuum generation to 8.5 μm in silicon-germanium waveguides. Optica, 5(4), 360-366.
36. Medjouri, A., Abed, D., Ziane, O., & Simohamed, L. M. (2018). Design and optimization of As2S5 chalcogenide channel waveguide for coherent mid-infrared supercontinuum generation. Optik, 154, 811-820.
37. Li, Z., Yuan, J., Mei, C., Li, F., Zhou, X., Yan, B., Wu, Q., Wang, K., Sang, X., Long, K. and Yu, C., (2019). "Multi-octave mid-infrared supercontinuum and frequency comb generation in a suspended As 2 Se 3 ridge waveguide." Applied Optics, 58(31), pp.8404-8410.
38. Lamont, Michael R. E., et al. "Supercontinuum generation in dispersion engineered highly nonlinear (γ= 10/W/m) As 2 S 3 chalcogenide planar waveguide." Optics Express 16.19 (2008): 14938-14944.
39. Almeida, V. R., Xu, Q., Barrios, C. A., & Lipson, M. (2004). "Guiding and confining light in void nanostructure." Optics letters, 29(11), 1209-1211.
40. Gehlot, K., & Sharma, A. (2016). "Optimization of Si slot waveguide using approximate semi-analytical method." Optics Express, 24(5), 4722-4729.
41. Zhang, L., Lin, Q., Yue, Y., Yan, Y., Beausoleil, R. G., & Willner, A. E. (2012). "Silicon waveguide with four zero-dispersion wavelengths and its application in on-chip octave-spanning supercontinuum generation." Optics express, 20(2), 1685-1690.
42. Karim, M. R., Ahmad, H., Ghosh, S., & Rahman, B. M. A. (2018). "Mid-infrared supercontinuum generation using As2Se3 photonic crystal fiber and the impact of higher-order dispersion parameters on its supercontinuum bandwidth." Optical Fiber Technology, 45, 255-266.
43. Karim, M. R., Al Kayed, N., Dey, G. K., & Rahman, B. M. A. (2020). "Design and analysis of suspended core channel waveguide made using As2Se3 glass system for mid-infrared supercontinuum generation." Journal of Optics, 23(1), 015504.
44. Karim, M. R., Rahman, B. M. A., & Agrawal, G. P. (2014). "Dispersion engineered Ge 11.5 As 24 Se 64.5 nanowire for supercontinuum generation: A parametric study." Optics Express, 22(25), 31029-31040.
45. Montesinos-Ballester, M., Lafforgue, C., Frigerio, J., Ballabio, A., Vakarin, V., Liu, Q., ... & Marris-Morini, D. (2020). "On-chip mid-infrared supercontinuum generation from 3 to 13 μm wavelength." ACS photonics, 7(12), 3423-3429.
46. Zhang, Y., Wu, J., Yang, Y., Qu, Y., El Dirani, H., Crochemore, R., ... & Moss, D. J. (2022). "Enhanced self-phase modulation in silicon nitride waveguides integrated with 2D graphene oxide films." IEEE Journal of Selected Topics in Quantum Electronics.
47. Saini, T. S., Tiwari, U. K., & Sinha, R. K. (2017). "Rib waveguide in Ga-Sb-S chalcogenide glass for on-chip mid-IR supercontinuum sources: design and analysis." Journal of Applied Physics, 122(5), 053104.
48. Yu, Y., Gai, X., Ma, P., Vu, K., Yang, Z., Wang, R., ... & Luther-Davies, B. (2016). "Experimental demonstration of linearly polarized 2–10 μm supercontinuum generation in a chalcogenide rib waveguide." Optics Letters, 41(5), 958-961.
49. Saini, T. S., Hoa, N. P. T., Nagasaka, K., Luo, X., Tuan, T. H., Suzuki, T., & Ohishi, Y. (2018). "Coherent midinfrared supercontinuum generation using a rib waveguide pumped with 200 fs laser pulses at 2.8 μm." Applied Optics, 57(7), 1689-1693.