Application Note #1
Mid infrared supercontinuum generation

There has been growing interest in producing supercontinuum (SC) sources with high brightness and broad mid-infrared (MIR) spectral coverage for applications such as spectroscopy [1]; metrology [1]; and optical coherence tomography [2]. Especially important are sources that emit across the functional group region (2.5-6.6 µm) and the molecular fingerprint band (~6.6-20 µm) where almost all molecules can be identified via their characteristic absorption features. Whilst the 10+ µm range will be important in the longer term, many biological materials can be distinguished using their absorption spectra in the 2.5-10 µm range and, hence, sources reaching 10 µm provide adequate performance for many micro-spectroscopy applications [3,4]. An important practical factor is that the pulse peak power required to generate the SC should be relatively low (a few kW) so that relatively low cost, compact industrial style MHz repetition rate pump sources with tens or hundreds of mWs of average power can be employed.

Heavy metal glasses possess both wide MIR transparency and high third order optical nonlinearities. There are multiple MIR SC reports using Fluoride or Tellurite [9-11] fibers in which the spectrum extended up to the material transmission limit (~5µm). Chalcogenide glasses transmit to even longer wavelengths and also offer higher nonlinearities [12] and, thus, many SC demonstrations using chalcogenide fibers have been reported quite recently [13-17], however, few of these reach the transmission limit of the materials.

It is now established that spectrum extension to ~10 µm requires a long pump wavelength (3-5 µm) [5,19]. MIROPA is therefore an ideal source for generating MIR SC allowing pumping at wavelengths in the 3-4.5µm range, and has already been used in multiple fibers and waveguide demonstrations.

For example, using MIROPA an SC spanning 1.8-10µm with >10 mW average power was generated from a step index chalcogenide fiber using only a few-kW pulses at ~4 µm at 21 MHz repetition rate using a Spectra-Physics femtotrain pump laser [21]. More recently a linearly-polarized supercontinuum spanning 2-10µm was generated using a chalcogenide rib waveguide [[22] and Figure 1].

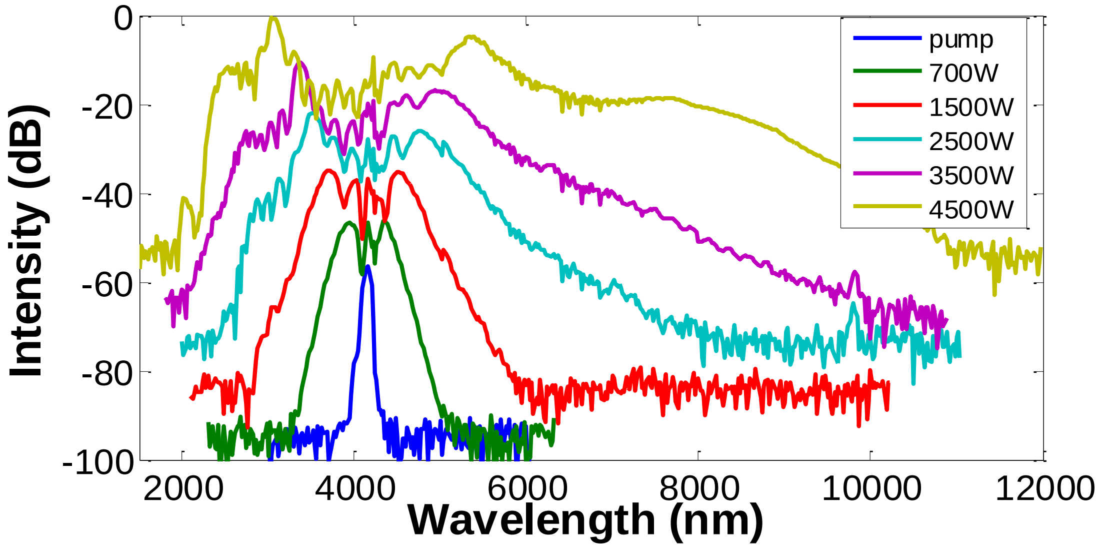

Figure 1: Typical spectra emitted from a 1.8cm long chalcogenide glass waveguide pumped by 320fs duration pulses at 4.184µm.as a function of the peak power coupled into the waveguide.

In general, for pulses >≈150fs in duration the generated supercontinuum is not completely coherent and hence exhibits shot to shot amplitude fluctuations of the spectral components. This makes it necessary to use a dual beam arrangement with signal and reference channels recorded simultaneously to perform spectroscopy. Since in a circular fiber the polarization state can also fluctuate a linearly polarized spectrum becomes a distinct advantage since it provides a stable relation between signal and reference signals produced using a simple angled beam splitter.

Examples of the SC spectra produced by waveguide for different pump powers at 4.184µm are shown in figure 1. The waveguide is a quasi-single mode design and emits in the fundamental mode at all wavelengths leading to a diffraction-limited source focusable to a spot ≈wavelength in diameter across its full spectral range. As a result the emission has a spectral brightness 100-1000x greater than the infrared beam line of a typical synchrotron.

Utilizing the linearly polarized SC source we constructed a simple dual beam spectrophotometer using a 45°beam splitter with a conventional 0.25m monochromator. To demonstrate the dynamic range and stability we recorded a simple high resolution (~5nm resolution bandwidth) transmission spectrum of a ~0.5mm thick polystyrene sample and compared this with a conventional glowbar source in an FTIR. These two sources have similar average power in the beams passing through the sample but the SC is around 10^5 times brighter indicating that the same signal to noise performance would be obtained when the beam were focused to provide wavelength scale resolution. The SC source also provided higher dynamic range and resolved the known features at ~3450nm in the spectrum ~10dB below the noise floor of the FTIR.

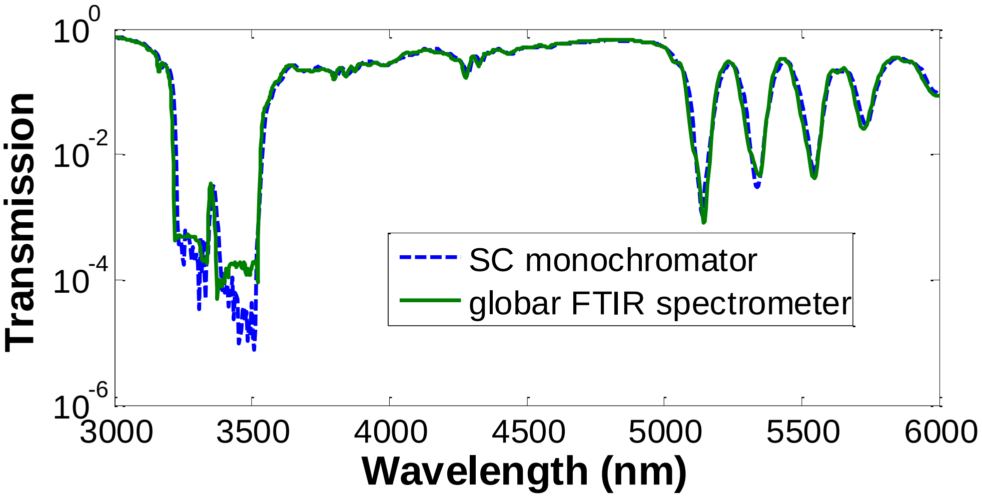

Figure 2: a dual beam spectrophotometer measurement of a polystyrene sample obtained using the SC source (blue) and a glowbar source (green). The SC source exceeds the brightness of the glowbar by >10^4.

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References

1. K. Ke, C. A. Xia, M. N. Islam, M. J. Welsh, and M. J. Freeman, Opt Express 17, 12627 (2009).
2. Schliesser, N. Picque, and T. W. Hansch, Nat. Photonics 6, 440 (2012).
3. S. Colley, J. Hebden, D.. Delpy, A. Cambrey, R.Brown, E. Zibik, W. Ng, L. Wilson, and J. Cockburn, Rev. Sci. Instrum. 78, 123108 (2007).
4. P. Garidel and M. Boese, Microsc Res Techniq 70, 336 (2007).
5. B. J. Davis, P. S. Carney, and R. Bhargava, Anal Chem 82, 3487 (2010).
6. Y. Yu, X. Gai, T. Wang, P. Ma, R. P. Wang, Z. Y. Yang, D. Y. Choi, S. Madden, and B. Luther-Davies, Opt Mater Express 3, 1075 (2013).
7. M. Liao, W. Gao, T. Cheng, X. Xue, Z. Duan, D. Deng, H. Kawashima, T. Suzuki, and Y. Ohishi, Appl Phys Express 6, 032503 (2013).
8. J. J. Pigeon, S. Y. Tochitsky, C. Gong, and C. Joshi, Opt. Lett. 39, 3246 (2014).
9. C. Petersen, U. Møller, I. Kubat, B. Zhou, S. Dupont, J. Ramsay, T. Benson, S. Sujecki, N. Abdel-Moneim, Z. Tang, D.Furniss, A. Seddon and O. Bang, Nat Photonics 8, 830 (2014).
10. G. Qin, X. Yan, C. Kito, M. Liao, C. Chaudhari, T. Suzuki, and Y. Ohishi, Appl. Phys. Lett. 95, 161103 (2009).
11. P. Kulkarni, V. Alexander, M. Kumar, M. Freeman, M. N. Islam, F. L. Terry, M. Neelakandan, & A. Chan, J. Opt. Soc. Am. B 28, 2486 (2011).
12. P. Domachuk, N. Wolchover, M. Cronin-Golomb, A. Wang, A. George, C. Cordeiro, J. Knight, and F. Omenetto, Opt. Express 16, 7161 (2008).
13. B. J. Eggleton, B. Luther-Davies, and K. Richardson, Nat. Photonics 5, 141 (2011).
14. Mouawad, J. Picot-Clemente, F. Amrani, C. Strutynski, J. Fatome, B. Kibler, F. Desevedavy, G. Gadret, J. C. Jules, D. Deng, Y. Ohishi, and F. Smektala, Opt Lett 39, 2684 (2014).
15. R. R. Gattass, L. B. Shaw, V. Q. Nguyen, P. C. Pureza, I. D. Aggarwal, and J. S. Sanghera, Opt Fiber Technol 18, 345 (2012).
16. D. D. Hudson, M. Baudisch, D. Werdehausen, B. J. Eggleton, and J. Biegert, Optics Letters 39, 5752 (2014).
17. F. Théberge, N. Thiré, J.-F. Daigle, P. Mathieu, B. E. Schmidt, Y. Messaddeq, R. Vallée, and F. Légaré, Optics Letters 39, 6474 (2014).
18. T. Cheng, Y. Kanou, X. Xue, D. Deng, M. Matsumoto, T. Misumi, T. Suzuki, and Y. Ohishi, Optics Express 22, 23019 (2014).
19. J. S. Sanghera, L. B. Shaw, and I. D. Aggarwal, Ieee J Sel Top Quant 15, 114 (2009).
20. Y. Yu, X. Gai, P. Ma, D. Y. Choi, Z. Y. Yang, R. P. Wang, S. Debbarma, S. Madden, and B. Luther-Davies, Laser Photonics Rev 8, 792 (2014).
21. Y. Yu, B. Zhang, X. Gai, C. Zhai. S. Qi, W. Guo, Z. Yang, R. Wang, D. Choi, S. Madden, B. Luther-Davies, Optics Letters 40, 1081-1084 (2015).
22. Y. Yu, X. Gai, P. Ma, K. Vu, Z. Yang, R. Wang, D. Choi, S. Madden, B. Luther-Davies, Optics Letters (in press) (2016).