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# High power, ultra-broadband supercontinuum source based on highly GeO<sub>2</sub> doped silica fiber

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## Abstract

We demonstrate a 74 mol % GeO<sub>2</sub> doped fiber for mid-infrared supercontinuum generation. Experiments ensure a highest output power for a broadest spectrum from 700nm to 3200nm from this fiber, while being pumped by a broadband 4 stage Erbium fiber based MOPA. The effect of repetition rate of pump source and length of Germania-doped fiber has also been investigated.

Further, Germania doped fiber has been pumped by conventional Silica based photonic crystal fiber supercontinuum source. At low power, a considerable broadening of 200-300nm was observed. Further broadening of spectrum was limited due to limited power of pump source. Our investigations reveal the unexploited potential of Germania doped fiber for mid-infrared supercontinuum generation. This measurement ensures a possibility of Germania based photonic crystal fiber or a step-index fiber supercontinuum source for high power ultra-broad band emission being pumped a 1060nm or a 1550nm laser source. To the best of our knowledge, this is the record power, ultra-broadband, and all-fiberized SC light source based on Silica and Germania fiber ever demonstrated to the date.

**Keywords:** Fiber amplifiers, Large mode area fibers, Er-doped fibers, High power lasers.

## 1. INTRODUCTION

Fiber based Supercontinuum (SC) sources are great sources of light, as they offer a wide range of wavelengths, good beam quality, high spectral density, and compact size device. Silica based photonic crystal fibers (PCF) have been used as non-linear medium for spectral broadening successfully. However due to high phonon energy of silica glass broadening limits up to 2.7  $\mu\text{m}$ . Another alternative option for further broadening is Germania (GeO<sub>2</sub>) based glass [1]. Although developments in Germania based fiber has been limited due to two reasons. First, due to the significant difference between thermal expansion coefficient of Silica and Germania, it is quite difficult to fabricate a heavily GeO<sub>2</sub> doped core fiber. Secondly, there is a lack of suitable pump laser sources emitting near zero dispersion wavelength (ZDW) of highly GeO<sub>2</sub> doped fibers, where ZDW is normally larger than 1.6  $\mu\text{m}$ . Initial attempts of SC generation in highly doped GeO<sub>2</sub> fiber involve a 2  $\mu\text{m}$  laser as a pump source, which limits the blue edge of the spectrum above 1.7  $\mu\text{m}$  [2]. Recently, Yang *et al.* claimed a pure Germania core fiber with a 1.426  $\mu\text{m}$  ZDW and demonstrated a 10 dB bandwidth from 717 nm to 2998 nm but output power was limited to 350 mW [3]. In this paper, we report a SC based on a 74 mol % GeO<sub>2</sub> doped core fiber, which is being pumped by a broadband 4-stage Er-Yb fiber based master oscillator power amplifier (MOPA). We use a high power, in-house constructed 4-stage MOPA based on Er-Yb based fiber, this source emits over a broadband range thanks to the in-amplifier spectral broadening. This versatile broadband source is quite suitable for efficiently pumping any Ge-doped fiber having ZDW larger than 1.4 $\mu\text{m}$ . To the best of our knowledge, this is a record power for an ultra-broadband, all-fiberized, and compact device size SC light source based on Silica and Germania fiber, ever demonstrated to date.

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## 2. PUMP SOURCE AND GeO<sub>2</sub> DOPED FIBER

An all-fiberized compact 4-stage MOPA was constructed in-house, a diode laser being directly modulated was used as a seed source. The pulse width was fixed to 1 ns (+/- 100 ps) and frequency could be varied from 10 KHz to 20 MHz. The signal was further amplified in 3 stages. Figure 1(a) shows the pump power of final stage and final output power with respect to the pump current. A highest power of 13.17 W was obtained at 34 W of pump power with a nearly 40% slope efficiency. Figure 1(b) shows the output spectrum for three different pump currents 1 A, 4 A, and 8 A corresponding to 0.53 W, 6.39 W, and 13.17 W output power respectively. A heavily Germanium doped silica fiber, with GeO<sub>2</sub> molar concentration of around 74% was used in this work. This fiber was fabricated using optimized modified chemical vapor deposition (MCVD) process at COFT, NTU Singapore by Sidharthan et al. [4]. The fiber had a core diameter and NA of 3.5 $\mu$ m and 0.58 respectively, with a cladding diameter of 125 $\mu$ m. Figure 1(c) shows the schematic of the SC source where the delivery of pump source is spliced to Ge-doped fiber, the output end of fiber was cleaved to 8 degree to avoid any back reflection. The delivery fiber of the pump source is a standard PM-1550nm double clad passive fiber, which has a core diameter of 9 $\mu$ m with a NA of 0.12. The significant difference between core diameter and NA of the delivery fiber and the Ge-doped fiber leads to poor coupling efficiency.

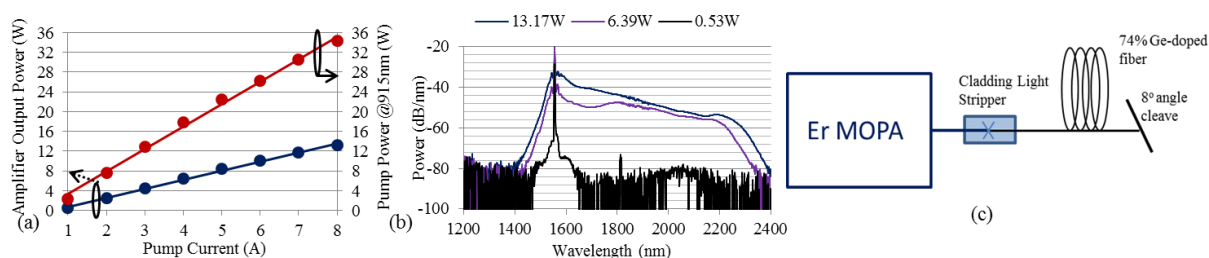


Fig. 1 (a) Output power and pump power with respect to pump current for a 4-stage Er-fiber based MOPA at 10MHz rep rate (b) output spectrum of Er-MOPA at different output power at 10MHz rep rate and (c) schematic of SC source.

## 3. SUPERCONTINUUM EXPERIMENTS

Figure 2 shows the output spectrum of SC source for different fiber lengths and different repetition rate of seed source at a constant current of 4 A through the pump diodes. Several fiber lengths of GeO<sub>2</sub> doped fiber were characterized, although only results for 22m, 5m, and 0.9m are being presented in Fig. 2(a), Fig. 2(b), and Fig. 2(c) respectively. This clearly shows the broader shift of red shift with shorter piece of fiber, revealing the importance of loss above 2.4 $\mu$ m. At higher repetition rate the total average power increases, as the MOPA runs more efficiently but when the repetition rate becomes high peak power is reduced which below some threshold limits the spectral broadening. The best results in terms of spectral broadening are achieved for 90 cm long piece, at 1MHz power, spectrum varies from 700 nm to 3200 nm. The total output power at 6 A pump current is 1.44 W, power above 1650 nm is 760 mW, and power above 2400 nm is 225 mW. To the best of our knowledge, this is the highest output power demonstrated for a broadest supercontinuum source based on Silica and Germania fiber. This can be an ideal source for pumping a ZBLAN and InF fiber for further extending the spectrum into 4 to 5  $\mu$ m range. Unfortunately, the potential of high power of MOPA remains unexploited due to strong mismatch between core diameter of delivery fibers and Germania doped fiber.

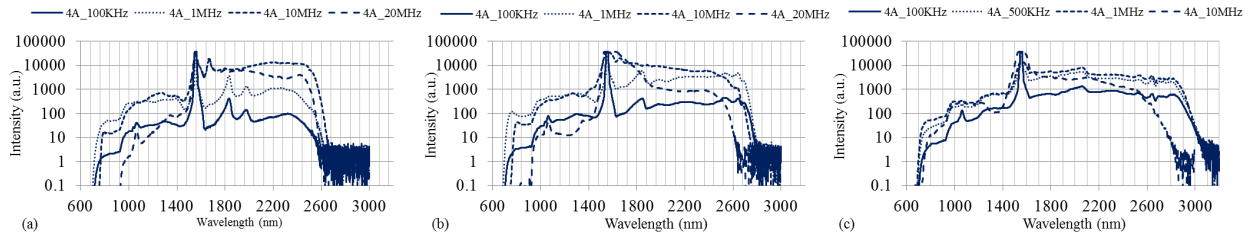


Fig. 2 Output spectrum of SC source at 4A pump current (corresponding to output power 6.39W at 10MHz rep rate) for different rep rates and different length of GeO<sub>2</sub> doped fiber (a) 22m (b) 5m (c) 0.9m long fiber.

Further in order to judge the potential of a Germania doped PCF, a commercially available Silica PCF based SC source was used to pump a 4 m long Germania fiber. Figure 3(a) shows the output spectrum of both Silica-PCF source and GeO<sub>2</sub>-fiber pumped by Silica PCF source for different current levels of pump source of Silica-PCF SC source. Clearly extension of the red edge can be noticed. A gain of 200nm to 300nm spectral width was observed. The Silica PCF was butt coupled to Germania fiber, a coupling efficiency of 60% was observed although power level above 1650nm remains almost same. This ensures the extension of power from 1060nm towards longer wavelengths. However, due to limited power, extension of power remains limited to 2500nm, which can be further extended by increasing peak power or changing the pulse width.

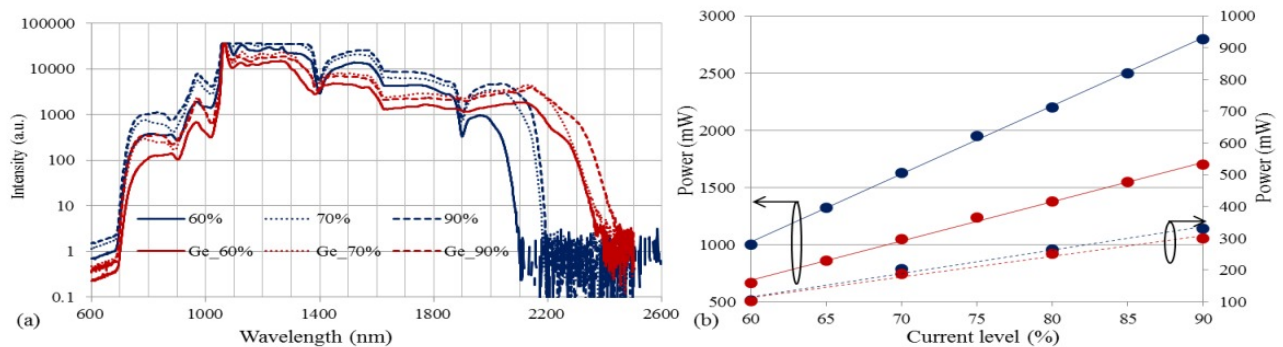


Fig. 3(a) Output spectrum of PCF-1060nm SC source and Ge-PCF-1060nm SC at different seed current (b) Output power of full spectrum and above 1650nm for both PCF-SC and Ge-PCF-1060nm SC source.

## 5. CONCLUSION

We demonstrate highest output power for a broadest supercontinuum source based on Silica and Germania fiber in an all fiberized and compact size device. Our investigations reveal the unexploited potential of Germania doped fiber for mid-infrared supercontinuum generation.

## 5. ACKNOWLEDGEMENT

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