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Supercontinuum fiber laser source for water quality and heavy metals detection

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We report a compact, all fiber, 150 ps fiber master oscillator power amplifier operating at 1064 nm that has the ability of producing a maximum average output power of 2.16 W with peak power as high as 10 kW. The output from the master oscillator power amplifier is spliced with a highly nonlinear photonic crystal fiber, generating a supercontinuum with an average power of 250 mW at repetition rate of 1 MHz and spectrum bandwidth spanning from 600 to 1700 nm. The developed supercontinuum system is used to detect the presence of heavy metal contaminants in water by a simple light transmittance method to ensure that the water is free from heavy metal contaminants and safe for consumption. The supercontinuum laser source was shone onto a water sample with a detector placed at another end in order to measure the transmitted supercontinuum light. By measuring the amount of light attenuated at particular wavelength, the concentration of heavy metal contaminants present in the water sample could be determined.

Keywords: supercontinuum generation, master oscillator power amplifier, nonlinear optics, transmittance measurement, heavy metal contaminants.

1. Introduction

Supercontinuum (SC) is an interesting topic to be discussed and researched due to the introduction of a photonic crystal fiber (PCF) that poses high nonlinearity characteristics. The applications of SC range from spectroscopic and microscopic measurement to a biomedical field [1]. The generation of SC involves an initial narrow bandwidth pulse undergoing conversion of frequency along with high nonlinearity when being pumped into a PCF resulting in a broadband spectrum spanning across the ultraviolet (UV) to infrared (IR) regions.

In recent years, a number of researches have been conducted to generate SC, either in continuous wave (CW) regime or pulsed laser regime. SC generated by a CW fiber laser has higher spatial and spectral density of radiation, which leads to higher average power compared to a pulsed laser [2]. TRAVERS *et al.* have demonstrated supercontinuum generation with the average power of 50 W, spanning across 1.06 to 2.2 μm by a 400 W single mode, continuous wave, ytterbium fiber laser [3]. Besides, CUMBERLAND *et al.* have reported a 29 W supercontinuum spanning from 1.06 to 1.67 μm by using a 50 W CW Yb fiber laser [4].

However, CW-pumped SC has a drawback of relatively high (20% to 30%) energy fluctuations of the SC pulses. Moreover, since the time structure of CW-pumped SC radiation is irregular, applications relating to telecommunications, metrology of optical frequencies and time-resolved spectroscopy are not suitable for such generation regime [2]. In order to overcome the problem mentioned above, a generation of SC by pumping an ultra-short pulsed fiber laser into PCF is employed. WADSWORTH *et al.* have demonstrated a broad, flat supercontinuum extending from 0.5 μm to beyond 1.75 μm by a sub-nanosecond pump source at 1.06 μm [5]. PRICE *et al.* have reported an ultra -broad supercontinuum generation in a holey fiber by a diode pumped, ytterbium doped fiber source operating at 1.06 μm [6]. An experimental demonstration of a white light supercontinuum generation extending from 0.4 to 0.7 μm using the fundamental and second harmonic signals of a passively *Q*-switched microchip laser was reported by CHAMPERT *et al.* [7]. STONE and KNIGHT have demonstrated on a visibly white supercontinuum generation extending from below 400 to 2450 nm by pumping a sub-nanosecond pump source at 1.064 μm in a photonic crystal fiber [8]. KUDLINSKI *et al.* presented the generation of supercontinuum with both nanosecond and picosecond sources at 1.064 μm. The spectra have spectral width extending from 0.372 μm to beyond 1.75 μm [9]. STARK *et al.* reported the formation of ultra-broad supercontinuum down to 280 nm in the deep UV by pumping a tapered photonic crystal fiber with 130 fs, 2 nJ pulses at 800 nm [10]. In addition, there are also articles regarding a generation of SC by using a master oscillator power amplifier (MOPA). The MOPA architecture involves the generation of high average powers from fibers by feeding a low power seed laser into a series of cascaded fiber amplifying stages in order to intensify the optical signal power to the desired level [11]. CHEN *et al.* have reported a picosecond fiber MOPA pumped supercontinuum source with average power of 39 W, spanning at least 0.4 to 2.25 μm [12]. HONGWEI CHEN *et al.* have demonstrated a 35 W high power all fiber supercontinuum system that covers the spectral range from 0.6 μm to beyond 1.7 μm by pumping a photonic crystal fiber with a picosecond fiber MOPA [13]. Finally, XIAOHONG HU *et al.* have delivered the generation of supercontinuum with average power of 49.8 W spanning from around 500 nm to above 1700 nm by a 1.05 μm picosecond pulsed fiber MOPA system [14].

Since the broadband SC laser system spans an equal power across an ultraviolet (UV), visible (VIS), and infrared (IR) region, it is suitable to be used for characterization of the quality of river or lake water by using a spectroscopy method. Specifically, it is possible to detect the presence of heavy metal contaminants in water. Heavy metal contaminants are highly toxic substances and harmful when consumed excessively. Furthermore, they are also one of the root causes for pollution to the environment. By shining the SC onto the water sample and placing a detector at the other end of the water sample, we would be able to detect the transmitted intensity of the SC light. By comparing the transmittance of water samples with and without the presence of heavy metal across the broad spectrum, we can determine the absorption of particular heavy metal contaminants at certain wavelength and subsequently find out the concentration of heavy metal contaminants present in the river with respect to the attenuated transmitted signal. This will be useful in determining whether the river water is safe for consumption.

Here we report the generation of broadband SC by a compact, all fiberized gain switched seeded MOPA generating train of optical pulses in the picosecond range at 1.06 μm spliced with 15 m long of highly nonlinear PCF. In our MOPA configuration, a low power gain switched laser diode was used to produce optical pulses with 150 ps pulse width. The laser diode was subsequently connected with a series of amplifier stages which provided a gain in order to boost the signal power to a desired level. As a result, this compact, all-fiber MOPA is capable of producing an output average power of 2.16 W at the repetition rate of 4 MHz, which is equivalent to 3.6 kW of peak power. On the other hand, when the repetition frequency is reduced to 1 MHz, the average output power generated is 1.6 W, with peak power of 10.6 kW. The MOPA output was fusion spliced with a 15 meters long of PCF and consequently, a broad continuum was observed covering the spectrum range of 600 to 1700 nm. This SC laser system is highly suitable for spectroscopy application in determining the contaminants in river or lake water. Compared to a conventional SC laser which produces the output as high as 39 W [12], our SC laser system has an average output power of around 250 mW, which is appropriate for water contamination detection without damaging the photodetector. Moreover, since the system that we built is in compact, all-fiber mode, we show that a portable system which is suitable to be carried to the measuring site to perform *in situ* measurement is achievable.

2. Experimental setup

The experimental setup is constructed as shown in Fig. 1. A gain-switched laser diode serves as a seed laser for the MOPA. The MOPA is capable of operating in two different pulse repetition frequencies, 4 and 1 MHz. At both frequencies, a train of stable optical pulses with 150 ps pulse width was generated by the seed laser. The output of the seed is then fed into two cascaded preamplifier stages along with a power amplifier stage, forming the MOPA. The first preamplifier employed bi-directional, core pumping configuration. A 4.5 meters of Yb-doped fiber (5 μm core and 130 μm cladding diameters) which serves as a gain medium was pumped by two 975 nm single mode pump diodes with maximum power of 160 mW each. A total gain of 15 dB was achieved in this stage. Then, the second preamplifier stage employs a similar Yb-doped active fiber used in the first preamplifier stage (5 μm core and 130 μm cladding diameters). How-

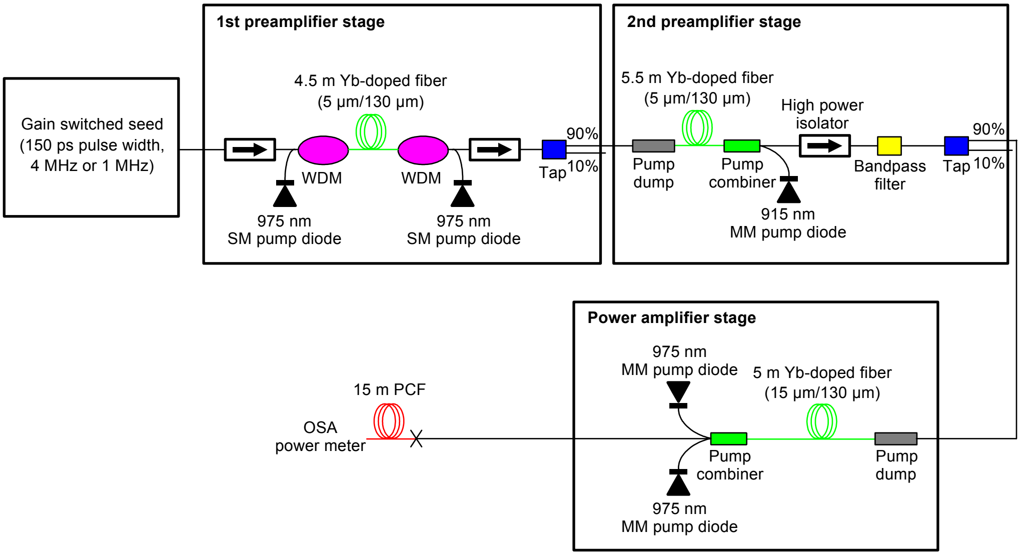

Fig. 1. The schematic of a MOPA spliced with PCF forming SC laser system.

ever, the cladding pumping in this stage was done in the backward direction, through a fiberized pump combiner in order to minimize the spectral broadening as a result of self-phase modulation (SPM) as well as suppressing any possible stimulated Raman scattering (SRS) generation. By pumping the 5.5 m long Yb-doped fiber with a multimode 915 nm laser diode that has a maximum power of 10 W, a total gain of 16 dB was achieved at this stage. A 10% monitor tap was spliced at the end of both the 1st and 2nd preamplifiers in order to observe the waveform of the system without damaging the photodetector.

The output was then connected to the final power amplifier stage that employs 5 m long large mode area (LMA) Yb-doped gain fiber with core and cladding diameter of 15 and 130 µm, respectively. Nonlinear effects such as SPM and SRS could be reduced by using a bigger core diameter fiber [11]. The cladding absorption is 5.40 dB per meter at 976 nm and the estimated total pump absorption is 27 dB across 5 m length of doped LMA. Potential SPM and SRS could be further reduced by pumping the gain medium in the backward direction with two 975 nm multimode pump diodes that are capable of producing 10 W maximum power individually. The total gain achieved in this stage is 13 dB.

The output of the MOPA was fusion spliced with a 15 m long PCF. The PCF used in this experiment was custom made for this experiment with core and cladding diameters of 4.8 and 125 µm, respectively, as well as numerical aperture (NA) of 0.2. Moreover, it operates at a single mode with zero-dispersion wavelength of 1040 nm. Therefore it allows nonlinear an efficient broadening of spectrum of pump source wavelength of 1060 nm. The output from the PCF is then fed into an optical spectrum analyser (OSA) for spectrum measurement and an optical power meter for optical power measurement.

3. Result and discussion

The output from the gain switched laser seed was measured by a 5 GHz InGaAs photodetector (Thorlabs SIR5-FC). The photodetector receives and converts the optical signal from the laser seed into an electrical signal in order for the oscilloscope (Agilent Infiniium 86100D) to analyze and display the pulse. Figure 2 shows the normalized pulses produced by the laser seed in both repetition rates of 1 and 4 MHz. Both pulses have pulse widths of 150 ps.

A bandpass filter with the centre wavelength of 1064 nm and a passband of 5 nm is placed towards the end of the second preamplifier stage in order to filter out amplified spontaneous emission (ASE) components [15]. As indicated in Fig. 3, the red bold line is the output spectrum generated by the laser seed, whilst the green dashed line is the spectrum from the first preamplifier. It was observed that the preamplifier has generated unwanted ASE noise due to the low duty cycle operation from the seed laser. This ASE noise will affect the optical signal to noise ratio (OSNR) at the final amplifier and also will limit the total extractable pulse energy if it is not being suppressed. After

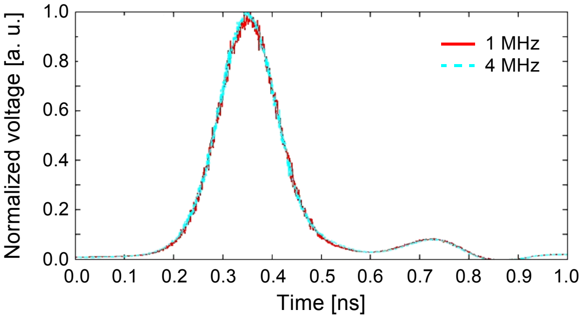

Fig. 2. Pulse shape of the laser seed with both repetition rates of 1 and 4 MHz; the pulse width is 150 ps.

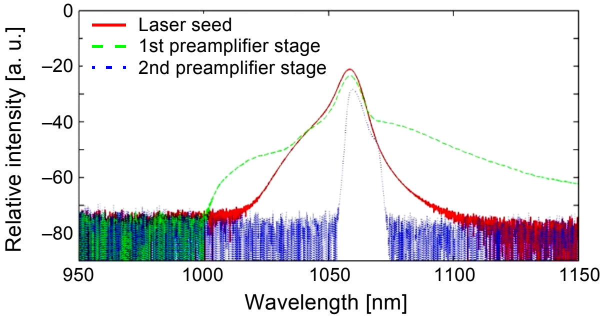

Fig. 3. Optical spectrum generated by laser seed, first preamplifier stage and second preamplifier stage.

passing through the second preamplifier stage, the OSNR improved significantly as shown by the blue dotted line.

The output optical power and spectrum are measured with Thorlabs power meter (PM100D) and Yokogawa optical spectrum analyser (AQ6370C), respectively. At 4 MHz repetition frequency, the laser seed produces an average output of 80 μW. After passing through the first preamplifier stage, the power increased to 2.55 mW. The signal is further amplified by second preamplifier stage to 103 mW. On the other hand, for 1 MHz repetition rate, the laser seed has a lower power, which is 26 μW. The first and second preamplifiers have allowed the average power to increase to 1 and 88.5 mW, respectively. Figure 4 shows the spectra evolution of both 4 and 1 MHz repetition rate at the power amplifier stage with increasing average power. The MOPA is capable of generating an average power of 2.16 W at 4 MHz. This is equivalent to peak power of 3.6 kW. Whilst for 1 MHz frequency, the peak power is increased to 10.6 kW compared to 4 MHz, but the average power generated is 1.6 W only. Unfortunately, as the frequency dropped from 4 to 1 MHz, nonlinear distortion of the spectra was observed. As shown in Figure 4**b**, with the same input pump power supplied by the 975 nm cladding pumped diodes, there is a significant broadening of spectrum at 1 MHz compared to 4 MHz. For repetition frequency of 4 MHz, the effect of SPM will cause a slight broadening of the spectrum as the power increases; whilst for repetition

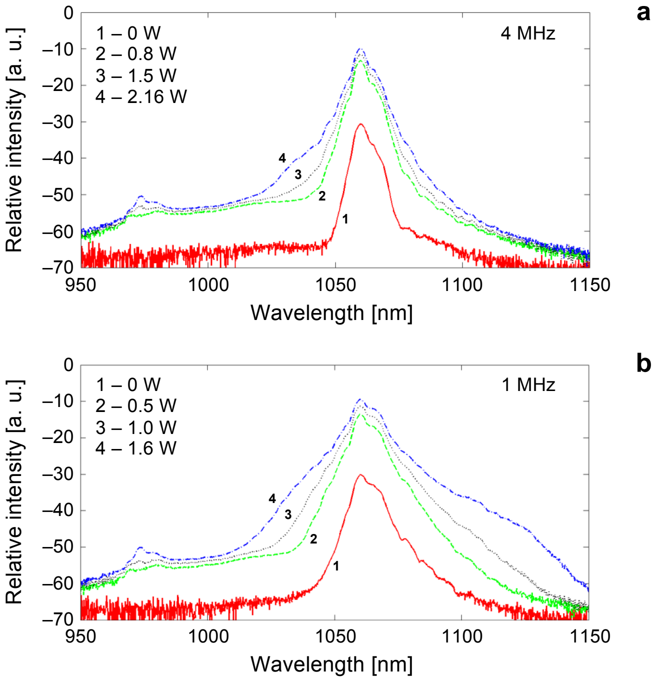

Fig. 4. Spectra measured at different power for 4 MHz (**a**) and 1 MHz (**b**) repetition rate.

rate of 1 MHz, there is a major expansion of the spectrum at the longer wavelength region (1100 nm) due to the introduction of SRS.

Most of the optical energies are confined within the optical laser peak which is at 1064 nm. Figure 5 shows the normalized linear scaled spectrum of the MOPA laser at the maximum power level (2.16 W at 4 MHz and 1.6 W at 1 MHz). The peaks at other wavelengths other than the optical signal cannot be seen in the linear scaled spectrum, indicating that the additional peaks are much lower than the main signal peak at around 1064 nm.

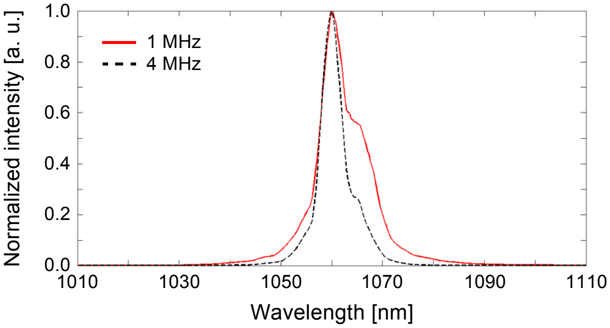

Fig. 5. The normalized linear scale spectrum of MOPA laser at maximum power for both 4 and 1 MHz.

The relationship between the average output power and the launched pump power at the power amplifier stage was plotted as shown in Fig. 6. The solid line indicates the best fit straight line for the repetition rate of 1 MHz, whilst the dashed line is the best fit straight line for 4 MHz repetition rate. From the figure we observed that the average power increases linearly as the launch pump power increases. There is no sign of power rolling off, and thus further increment of output power is still possible with the implementation of higher power pump diodes in the future [13].

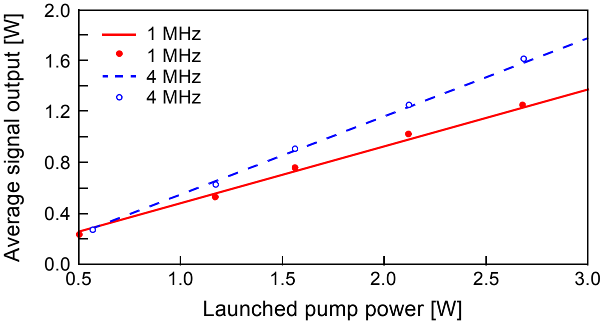

Fig. 6. Average signal output from MOPA against launched pump power of the pump diodes in power amplifier stage.

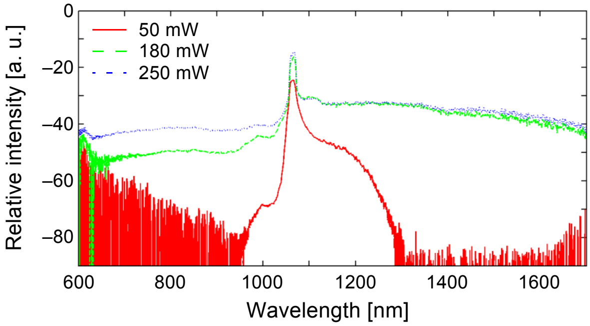

Fig. 7. Supercontinuum evolution in 15 meters PCF at output power of 50, 180 and 250 mW at a repetition rate of 1 MHz.

We obtained a continuum spectrum spanning across 600 to 1700 nm with the optical signal centred at 1060 nm as indicated in Fig. 7 and with the average output power of 250 mW. The reason 1 MHz repetition frequency was used to generate this broadband spectrum is due to its higher peak power compared to 4 MHz which leads to more effective conversion of the pump to visible wavelengths [12]. Due to the limitation of the OSA, we could measure the spectrum from 600 to 1700 nm only. We believe that the spanning range of the generated spectrum is larger than the measured value.

4. Application of developed SC laser system

The developed SC laser system is used for detection of heavy metal contaminants present in water by using a transmittance method. The SC light was shone onto a glass container filled with water samples to be tested, with a detector placed at another end of the container in order to collect the transmitted intensity of SC light. The optical path length is 10 cm. Due to the fact that different elements have their own individual absorption bands, by focusing on the wavelength where certain elements are sensitive, we could determine the presence of certain elements as well as their quantity by measuring the transmitted SC light intensity. Since the developed SC system spans from 600 to 1700 nm, we have a wide range of wavelengths available for the transmittance measurement.

Figure 8 indicates the original intensity spectrum of our SC laser source (solid line) along with transmitted SC spectrum of pure water (dashed line) at the wavelength range from 800 to 1000 nm. We observed that the transmitted intensity decreases with the presence of water. This is because a particular portion of the light is being absorbed by the molecules of water, allowing the remaining part of light to be transmitted through the solution. Note that the absorption varies across the wavelength. For instance, the absorption of water is the least at the wavelength around 900 nm, which results in the fact that most of the SC light is transmitted at that wavelength. On the other hand, the high

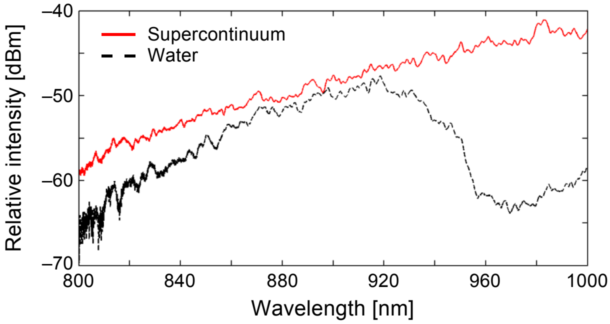

Fig. 8. Spectrum of supercontinuum with and without the presence of water across the wavelength 800 to 1000 nm obtained from optical spectrum analyser.

absorption at 960 nm wavelength region will cause most of the SC light to be absorbed and significantly decreases the intensity by approximately 20 dB.

Next, two different types of heavy metal contaminants, which are copper sulphate ($CuSO_4$) and ferric chloride ($FeCl_3$), were added into the water sample separately. The power intensity spectra of water mixed with different concentration of heavy met-

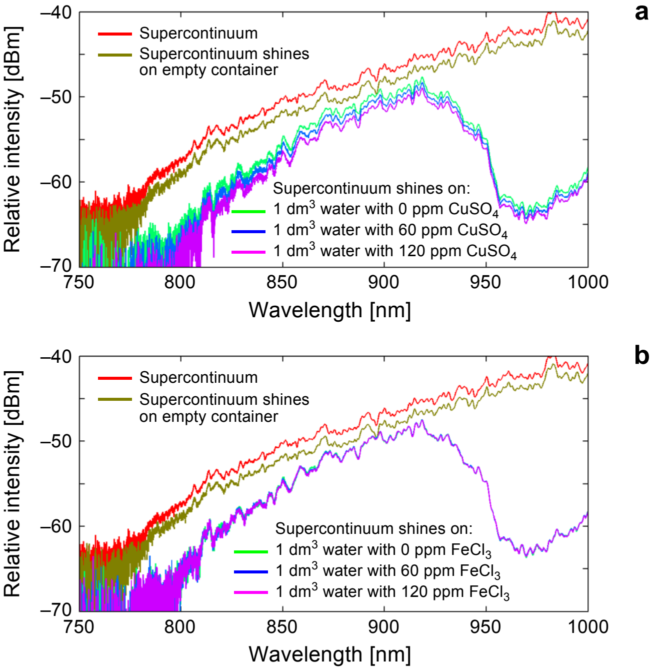

Fig. 9. Power intensity spectra of supercontinuum, with empty container in between, and with different concentration of copper sulphate (**a**) and ferric chloride (**b**) filled in water across the wavelength 750 to 1000 nm obtained from optical spectrum analyser.

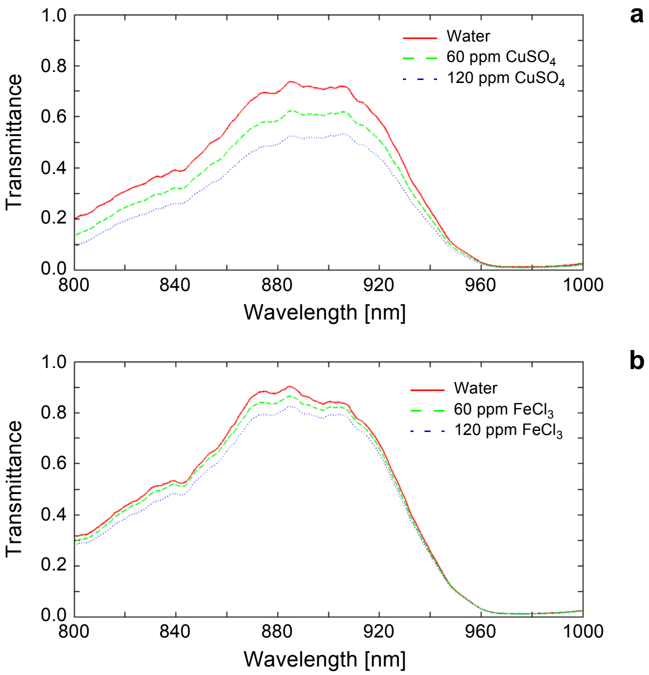

Fig. 10. Transmittance spectra of different concentration of copper sulphate (**a**) and ferric chloride (**b**) in water across the wavelength 800 to 1000 nm obtained from optical spectrum analyser.

al contaminants are recorded and shown in Fig. 9. We observed that as we introduced the heavy metal contaminants into the water sample, the power starts to fall across the wavelength. However, the trend of the spectrum is still with respect to the trend of water. Due to the difference in power intensity across the spectrum, it is necessary for us to transform the power spectrum into the transmittance spectrum for further analysis. The transmittance is defined as the ratio of transmitted intensity to initial intensity and the transmittance across 800 to 1000 nm was plotted as shown in Fig. 10. We discovered that the increment of concentration of contaminants has resulted in the dropping of the transmitted intensity. This is due to the rising of the amount of heavy metal molecules present in the water sample that absorb the light and preventing more light from transmitting. Moreover, it is also found that different contaminants have different absorbance. According to Figs. 10**a** and 10**b**, as the concentration of both copper sulphate and ferric chloride of equal amount are added into the water sample (60 and 120 ppm), copper sulphate tends to absorb more light than ferric chloride, which leads to smaller transmitted intensity obtained compared to ferric chloride solution. Furthermore, across the wavelengths 800 to 1000 nm, the transmittance of the water sample increases initially until it reaches the peak at around 880 nm and then starts to decrease vigorously until the transmittance is almost zero at 960 nm. The transmittance is best to be measured at the wavelength where the transmittance is stable and not fluctuating. Therefore, the best wavelength to measure the transmittance is from 860 to 920 nm.

5. Conclusion

An all-fiber MOPA laser system with 150 ps pulse width optical signal undergoing 44 dB of amplification spliced with a 15 m long PCF, yielding a broad continuum spectrum spanning across 600 to 1700 nm output was demonstrated. The MOPA system employed two different repetition frequencies, which are 4 and 1 MHz. It generated an average power of 2.16 W which corresponds to peak power of 3.6 kW at 4 MHz, whilst produced an average power of 1.6 W which is equivalent to 10.6 kW peak power at 1 MHz. The delivered SC laser system is suitable to be used for detection of heavy metal contaminants present in river or lake water due to its lower average power generated compared to conventional SC laser system.

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