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S + C + L BAND TUNABLE WAVELENGTH CONVERSION USING FWM DUAL-WAVELENGTH FIBER LASER IN A HIGHLY NONLINEAR FIBER

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ABSTRACT: *In this article, a novel wideband wavelength conversion is demonstrated using a highly nonlinear fiber consisting of a fluorine-doped fiber that has a high delta core and surrounded by a deeply depressed ring as opposed to the use of photonic crystal fibers. The wavelength conversion range is from 1460 to 1640 nm, which covers the S-, C- and L-bands of the optical network. The interacting waves consist of an arrayed waveguide grating tuned dual-wavelength fiber laser output together with a tunable laser source signal. A four-wave-mixing conversion of efficiency of −20 dB is achieved within a 70 nm tuning range within a 3.9 dB fluctuation. An optical signal to noise ratio of 30 dB is also realized within the same tuning range.* © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 55:379–382, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27284

Key words: *four wave mixing; dual-wavelength fiber laser; highly nonlinear fiber; four-wave mixing conversion efficiency*

1. INTRODUCTION

Nonlinear optical phenomenon has become an important technique in the generation of new frequencies which finds many applications in the area of parametric oscillation, multiwavelength fiber laser, and wavelength conversion. Lately, the interest in all optical wavelength converters is to create a new platform for all optical network system that will improve the network accessibility and flexibility and to reroute the data traffic without having to convert them into electrical format [1, 2].

Wavelength conversion is an essential technology for future switching architectures [3–5]. Several schemes, such as self-phase modulation, cross-phase modulation, cross-gain modulation, and cross polarization modulation [3], can be used to realize wavelength conversion. However, wavelength conversions based on a four-wave mixing (FWM) are one of the most promising methods, because it is fully transparent to the signal bit rate and modulation format [5, 6]. FWM can be performed in the semiconductor optical amplifier (SOA) or fiber. Generally, wavelength conversions based on the FWM in fiber can operate at a higher speed, whereas the speed of wavelength conversion in the SOA is rather limited due to a long response time of the carriers [5, 6].

FWM is a type of optical Kerr effect and occurs when light of two or more different wavelengths are launched into a fiber. Generally, in FWM light of three different wavelengths is launched into a fiber, giving rise to a new wavelength (know as an idler). The wavelength of the idler does not coincide with the other input signals. As an example, works by Lu et al. [7] and Yatsenko et al. [8] use tunable laser sources (TLSs) as their pump and signal as to obtain the new wavelength based on the FWM effect in highly nonlinear photonic crystal fibers (HNL-PCFs). Although the range achieved for wavelength conversion is wider, the experimental setup is elaborate and costly. Recent work [9, 10] uses similar configuration from a single ring to a double ring and having SOAs as the nonlinear gain medium for the observation of the FWM effect. Their range is limited to 40 nm only. As well as SOAs, a 100 m length of dispersion shifted fiber is also used as the nonlinear medium with a dual-wavelength fiber laser as the pump and signal source [11]. Their wavelength conversion range, however, is only limited to the C-band region.

In this article, we demonstrate a novel wideband wavelength conversion using a dual-wavelength fiber laser in a highly nonlinear fiber (HNLF) with a high nonlinear coefficient combined with a numerically small group dispersion velocity. The fluorine-doped fiber has a high delta core and is surrounded by a deeply depressed ring and thus is not based on the photonic crystal structures. This is an extension of our earlier work [12], which gives an interesting experimental result of a wide-band, tunable wavelength conversion range from 1460 to 1640 nm as it is to the author's knowledge the longest wavelength conversion and hopping range to date, based on simple HLNFs, although there are wider ranges that have been obtained using HNL-PCFs. In addition, the proposed setup uses an arrayed waveguide grating (AWG) that allows for efficient channel selection and therefore the highest wavelength conversion efficiency.

2. EXPERIMENTAL SETUP

Figure 1 shows the proposed ring cavity experimental setup which uses 11 m of Metrogain erbium-doped fiber (EDF) (DL1500L, Fibercore Ltd) as a medium source for amplified spontaneous emission (ASE) source as well as the gain medium. The EDF with Erbium ion concentration of 900 ppm has an absorption of 18.06 and 11.3 dB/m at 1530 and 980 nm, respectively. In this experimental setup, we demonstrate a high-power EDF amplifier (EDFA) pumped with 980 nm wavelength light from two semiconductor laser diodes (LDs). Light outputs from the two 980 nm pump LD modules are 215 mW each. They are combined using a polarization beam combiner. The output is then connected to the ring cavity via a 980/1550 nm wavelength division multiplexer coupler and directed into the ring cavity. The combined pump power that travels in a clockwise direction is then absorbed by the EDF. The erbium ions will be excited and will then reemit an optical output at 1550 nm in the form of ASE. From the measurement, the average ASE output power is 20.2 dBm with output emission in the C-band. The emission of C-band ASE output from the EDF will then travel through a 1 $\times$ 24 arrayed waveguide (AWG) which will be sliced into 24 individual output wavelengths coming from 24 channels. The 1 $\times$ 24 channels output covers a wavelength range of between 1530.473 and 1548.613 nm with an interchannel spacing of

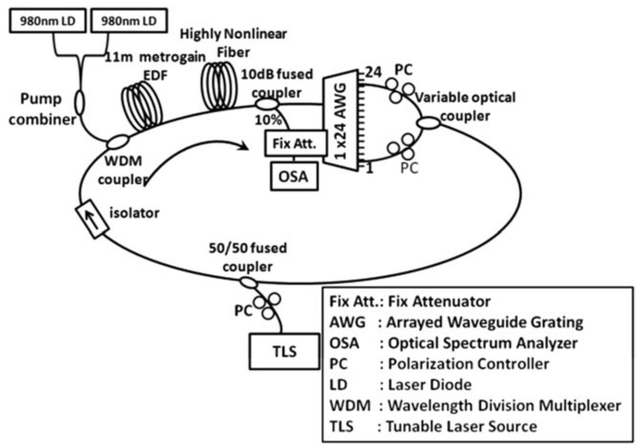


Figure 1 Schematic diagram for generating FWM effect in a highly nonlinear fiber using dual-wavelengths fiber laser incorporating AWG as a tuning element

100 GHz. The channels are then connected to the variable optical coupler via a PC (polarization controller) as illustrated in Figure 1. A PC is used to optimize the matching of the polarization state of pump and signal powers. The dual-wavelength fiber laser, which is generated at the output port of the 2 × 1 variable optical coupler, travels in the clockwise direction. This dual-wavelength output is then combined with the TLS output using a 50/50 fused coupler. This three-wavelength output will then be amplified by the EDFA and continue to travel toward the HNLF, where the interaction of the waves will result in the FWM effect.

The highest value of FWM conversion efficiency is selected by tuning the AWG's channel. This is one of the novelties of this configuration in which the dual-wavelength fiber laser can give the highest FWM conversion efficiency in the nonlinear fiber that can be selected independently as provided by the AWG channels. Through this selection, channels 11 and 15 give the highest value of FWM conversion efficiency when compared with other channels as shown in Figure 2.

Therefore, channels 11 and 15 that are at 1541.54 and 1538.3 nm are fixed as pump (P1) and signal (S) wavelengths, whereby the TLS acts as P2, which is tunable. The output power of the TLS [YOKOGAWA (AQ2200)] is set at 10.8 dBm and is tuned from 1400 to 1680 nm, with an output linewidth of 0.015 nm. The length of the HNLF is about 100 m, and its parameters are given in Table 1. The output from the HNLF is tapped by the 10% port of the 90/10 coupler where the larger portion of light is allowed to oscillate in the ring cavity. The output spectrum is measured using an optical spectrum analyzer (Yokogawa AQ6370B) with a resolution 0.02 nm.

TABLE 1 Fiber Parameters and Properties of Highly Nonlinear Fiber

Parameter	Unit	Value
Length, L	m	100
Dispersion @ 1550 nm, D_c	ps/nm km	0.15
Dispersion slope @ 1550 nm, $dD_c/d\lambda$	ps/nm^2 km	0.007
Zero dispersion wavelength, λ_o	nm	1531
Cut off wavelength	nm	1240
Effective area @ 1550 nm, A_{eff}	μm	12.3
Nonlinear coefficient estimated from effective area, γ	(W km)$^{-1}$	10.8
Fiber attenuation @ 1550 nm, α	dB/km	0.73
Total module loss @ 1550 nm	dB	0.15

3. RESULTS AND DISCUSSION

In this experiment, the generated triple wavelength is a combination of the dual-wavelength fiber laser and TLS that is shown in Figure 3 where it is marked as pump 1, signal and pump 2, respectively. Due to the beating of pump 1, signal and pump 2, they experience an index-modulated grating within the HNLF. This process generates two sidebands C2 (a conjugate of signal) and S2 (a replica of signal) around pump 2, spaced by Δf and having the states of polarization of pump 2. In our experiment, the intensities of C2 and S2 are measured for every different wavelength of pump 2 over the entire wavelength range of between 1460 and 1640 nm with 100 GHz of detuning depending on the spacing of the signal and pump 1. The intensities of two sidebands C2 and S2 also depend on the dual-wavelength operation where in this case channel 11 (1538.3 nm) and channel 15 (1541.5 nm) are pump 1 and signal, respectively. Figure 3 shows the output spectrum of the FWM after pump 1, signal and pump 2 copropagate through the HNLF with optical powers at 10.3, 5, and 3.86 dBm, respectively, and with pump 2 at 1530 nm.

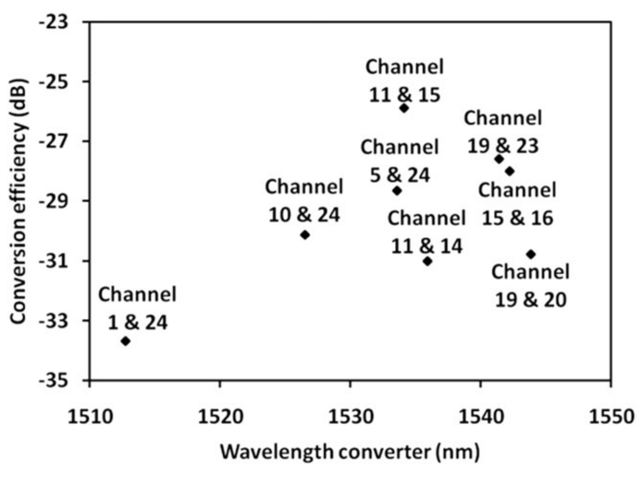


Figure 2 The value of FWM conversion efficiency for different AWG's channels

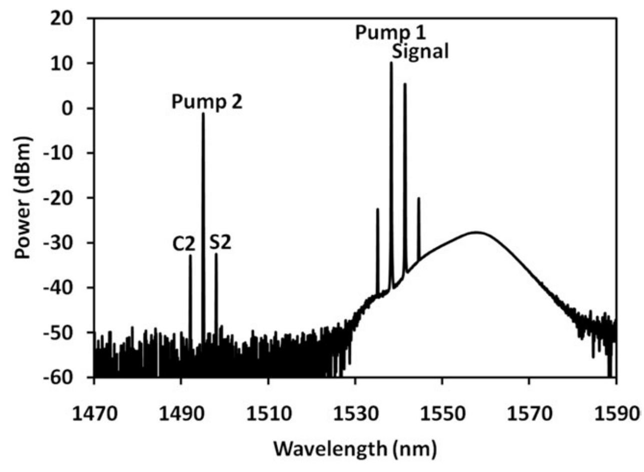
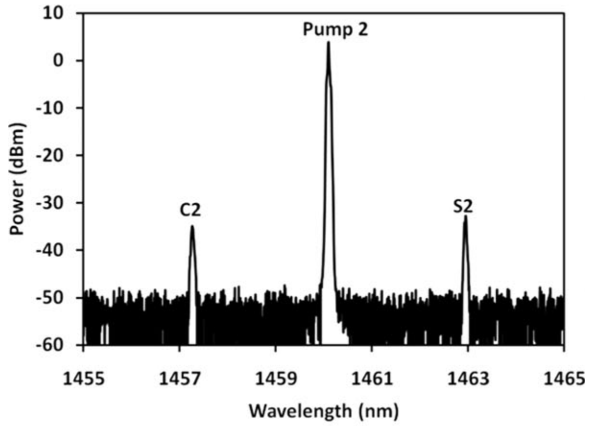
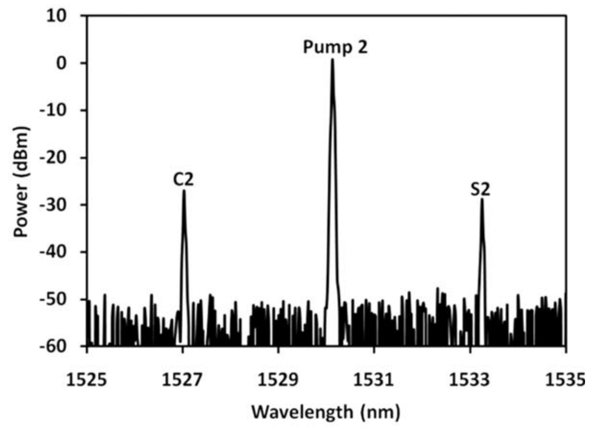


Figure 3 The typical output spectra at pump 1, signal and pump 2, as well as their converted signals (sideband fields) C2 and S2 when wavelength of pump 1, signal and pump 2 are 1538.3, 1541.5, and 1530 nm

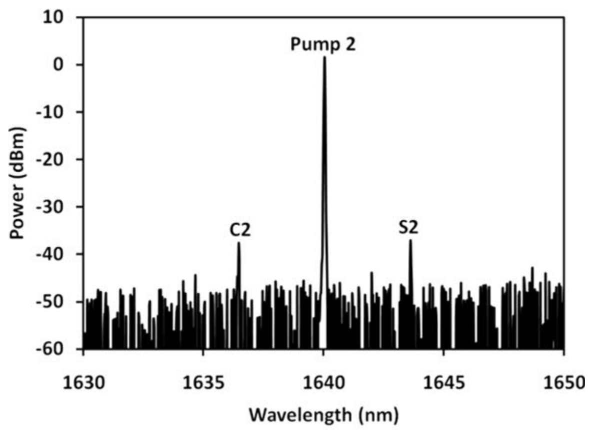
To investigate the tunability of the proposed wavelength conversion technique, the input powers of pump 1 and signal are fixed at 10.3 and 5 dBm, at wavelengths of 1538.3 and 1541.5 nm, respectively. The wavelength of pump 2 is then changed from 1460 to 1640 nm by using the TLS. The converted signals C2 and S2 are observed through the whole tuning range. Figures 4(a)–4(c) show the output spectra of S2, pump 2, and C2 at different wavelength values. Results presented below clearly show that by using the proposed configuration the ultra-broadband tunable wavelength converter with a tunable range of over 180 nm can be achieved.



(a)



(b)



(c)

Figure 4 The output spectra of S2, Pump 2 and C2 when the wavelength of Pump 1 and signal are 1538.3 and 1541.5 nm; (a) Pump 2 is 1460 nm and their input power is 3.86 dBm; (b) Pump 2 is 1530.2 nm and their input power is 3.00 dBm; (c) Pump 2 is 1640 nm and their input power is 3.36 dBm

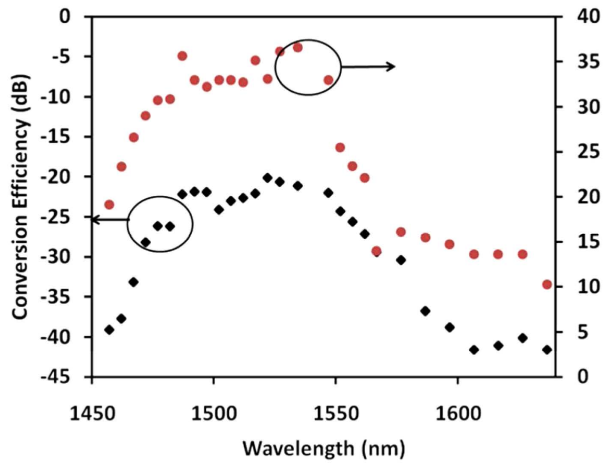


Figure 5 The conversion efficiency and the OSNR against the converted wavelength. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

The efficiency of the proposed configuration, characterization of FWM such as the conversion efficiency and the optical signal to noise ratio (OSNR) are measured from results shown in Figure 5. The conversion efficiency is obtained by changing the wavelength of pump 2 while fixing the input powers of pump1 of 10.3 dBm at 1538.3 nm and signal of 5 dBm at 1541.5 nm. During the measurement, the input pump power of pump 2 is about 3 dBm and its wavelength changes from 1460 to 1640 nm. The maximum power of the converted wavelength is obtained by adjusting the three PCs as shown in Figure 1 for each measurement. When the polarization state of either Pump 1 or signal is changed, the output power of both S2 and C2 changes significantly. When the polarization state of pump 1 and signal are both aligned and linear, the output powers of the converted signals are at maximum. Keeping this situation and by adjusting the PC and pump 2, a maximum output is achieved. The conversion efficiency is calculated as a ratio of the power of the converted signal C2 to the input signal. Results indicate that the FWM conversion efficiency is approximately −20 dB within 70 nm tuning range with 3.9 dB fluctuation. However, as the converted wavelength is tuned over 70 nm tuning range, the conversion efficiency drops rapidly due to the effect of chromatic dispersion in the fiber as stated by Inoue [13]. The figure also shows the OSNR versus wavelength shows that the OSNR being maintained above 30 dB at around 70 nm tuning range. The OSNR is stable within wavelengths of 1470–1550 nm and drops rapidly at longer wavelengths. This indicates that the data signal within this region can be converted efficiently. However, the application of conversion can still be realized at longer wavelengths with a higher degree of degradation. This can be improved by using higher pump and signal powers which cannot be realized at this moment due to the limitations of the high power laser.

4. CONCLUSION

In conclusion, an S+C+L band wavelength conversion by using FWM dual-wavelength fiber laser in a HNLF that operates with only one external pump laser (TLS) has been successfully demonstrated. Using the proposed method, a wide band wavelength conversion has been achieved with a range of 1460–1640 nm, giving a bandwidth of 180 nm. A four-wave-mixing conversion efficiency of −20 dB is achieved within a 70 nm tuning range within a 3.9 dB fluctuation. An OSNR of 30 dB is also realized within the same tuning range.

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HIGH-ISOLATION 2.4/5.2/5.8 GHZ WLAN MIMO ANTENNA ARRAY FOR LAPTOP COMPUTER APPLICATION

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ABSTRACT: *An isolation technique for two small-size triband wireless wide area network (WLAN) multiple-input multiple-output (MIMO) laptop computer antennas covering the 2.4/5.2/5.8 GHz bands is presented. The proposed WLAN MIMO antennas have measured isolation of better than −21 dB in the 2.4 GHz band and −32 dB in the 5.2/5.8 GHz bands in this study. In addition to enhanced isolation achieved, good antenna efficiencies of better than about 70 and 90%, respectively, in the 2.4 GHz and 5.2/5.8 GHz bands are obtained for the two antennas. The WLAN MIMO antenna array having a planar structure of size 9 × 55 mm2 is to be mounted at the top edge of the supporting metal plate of the laptop display. The two antennas can be fabricated at low cost on a thin FR4 substrate and are of a simple structure comprising a driven strip and a shorted strip, which provides two wide operating bands to cover the 2.4 and 5.2/5.8 GHz bands. Between the two antennas, there is an isolation element formed by a protruded ground plane and a spiral open slot embedded therein. The isolation element leads to enhanced isolation between the antennas in the 2.4/5.2/5.8 GHz WLAN bands and good antenna efficiencies for the antennas as well. Details of the isolation technique for the WLAN MIMO antennas are described, and the obtained results are presented and discussed.* Microwave Opt Technol Lett 55:382–387, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27279

Key words: *mobile antennas; wireless wide area network antennas; antenna isolation; multiple-input multiple-output antennas; laptop computer antennas*

1. INTRODUCTION

The 2.4/5.2/5.8 GHz tri-band WLAN (wireless wide area network) MIMO (multiple-input multiple-output) operation [1] has been demanded to achieve enhanced signal transmission and reception for mobile communications. For laptop computer applications, the WLAN MIMO operation requires a compact WLAN antenna array having enhanced isolation between the antennas and good radiation efficiencies for the antennas as well. The isolation techniques that have been reported for related applications include the use of a T-shaped ground plane between the antennas [2–6], a neutralization line connected between the antennas [7, 8], a ground wall and a connecting line added between the antennas [9], two planar inverted-F antennas with their shorting strips or plates oriented to face each other [10, 11], slot resonators embedded in the ground plane between the antennas to decrease the effects of the excited surface currents flowing from one port to another [12–14], and so on. However, the WLAN antennas applied in these studies may not be compact or suitable for the internal laptop computer antenna applications or the applied isolation techniques are not promising to achieve improved isolation in multiple operating bands.

Recently, to achieve enhanced isolation in the 2.4/5.2/5.8 GHz WLAN bands, the technique of applying a dual-band strip resonator disposed between two WLAN laptop computer antennas to trap the near-field radiation from one antenna to another has been reported [15]. The applied dual-band strip resonator can achieve isolation (S_{21}) better than −18 dB over the 2.4/5.2/5.8 GHz bands for the two WLAN antennas. To achieve a much enhanced isolation in the 2.4/5.2/5.8 GHz WLAN bands, we present in this article a new isolation technique of using an isolation element formed by a protruded ground plane and a spiral open slot embedded therein for a high-isolation WLAN MIMO antenna array. The measured isolation between antennas for the WLAN MIMO antenna array is better than −21 dB in the 2.4 GHz band and −32 dB in the 5.2/5.8 GHz bands in this study. In addition to much enhanced isolation between antennas, good antenna efficiencies of better than about 70 and 90%, respectively, in the 2.4 and 5.2/5.8 GHz bands are obtained for the two antennas. The proposed antenna array has a planar structure