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Generation of a multi-wavelength source spanning the entire C-band by nonlinear spectral broadening of dual-carrier electro-optic frequency combs

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Abstract: We demonstrate a multi-wavelength source with a high repetition rate of 25 GHz, spanning the entire C-band, of which 124 lines lie within 10 dB bandwidth. We exploit the spectral and temporal properties of dual carrier electro-optic combs to simultaneously enhance self-phase modulation (SPM) based broadening and increase the stimulated Brillouin scattering (SBS) threshold. Dual carrier combs are generated through electro-optic modulation of spectrally separated narrow linewidth carriers. They are spectrally broadened in a highly nonlinear fiber after amplification with an in-house built erbium ytterbium co-doped fiber amplifier. The temporal profile of the dual carrier combs consists of significantly narrow pulses (1.4-1.9 ps FWHM) in comparison to the single laser comb (16.5 ps FWHM), increasing the peak power and enhancing the SPM effects. Further, the spectral power is distributed across the comb lines, increasing the SBS threshold and thus the power scalability of the system. These two factors together boost the bandwidth of the spectrally broadened multi-wavelength source.

1. Introduction

Multi-wavelength sources play a vital role in a wide variety of applications such as optical carriers for high bandwidth communications, arbitrary RF waveform generation, astronomical spectrograph calibration and spectroscopy. Generation of optical carriers in conventional wavelength division multiplexing (WDM) and dense WDM (DWDM) implementations necessitates the use of individual laser sources requiring temperature and current stabilization for operating with precise wavelength and power. As the number of channels increase, this technique becomes infeasible due to increase in size, power consumption and cost (deployment and maintenance). A system with very few input lasers from which the remaining wavelengths are derived with equal channel separation would satisfy the bandwidth needs efficiently. Multi-wavelength sources have been previously demonstrated using mode-locked lasers [1], through various architectures utilizing electro-optic modulators [2–6] and through spectral broadening in highly nonlinear fiber (HNLF) [7]. Similariton [8] and soliton generation [9] in a fiber with tailored dispersion profile and Raman self-scattering in a dispersion decreasing fiber (DDF) [10] have also been used to implement multi-wavelength sources.

Among these, mode locked lasers suffer from instability and increased design and operational complexity at higher repetition rates. Moreover, they do not allow independent tuning of repetition rate (channel spacing) and central wavelength [11]. Modulation of continuous wave light, by an external electro-optic modulator, generates stable optical frequency comb at high repetition rates with tunable repetition rate and central wavelength. However, the comb bandwidth is

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mainly limited by the radio frequency (RF) bandwidth and power handling capability of the modulator used [12]. Cascading multiple modulators [12] to scale bandwidth is suitable for generating few tens of carriers but is inefficient for higher bandwidth requirements. This is because each additional modulator will only result in a linear increase in the bandwidth while needing additional RF components.

Nonlinear spectral broadening through cascaded four wave mixing (FWM) in optical fibers is an efficient technique to increase the number of carriers. Use of DDF as the non-linear media will result in increased noise due to modulation instability and requires optimization of dispersion slope [12]. Using HNLF will avoid the need to optimize dispersion slope, but the broadening is less. Multi-wavelength sources have been generated by using multiple stages of HNLF with SMF compression stages in between [7,11]. Though they realize wide bandwidths, the spectrum has degraded flatness. Nonlinear spectral broadening can be combined with electro-optic modulation to scale the number of carriers [13]. In [13], tailored RF waveforms are required to produce flat combs and the spectrum is discontinuous with large gaps between parts of spectrum generated by various orders. Though within an FWM order, the spectrum is continuous with good flatness, the bandwidth is limited. Hence it cannot be used as a single system that provides all the carriers across the C-band for DWDM based optical communication systems. Moreover, it requires the length of the SMF to be changed with change in repetition rate.

The attainable bandwidth of the multi-wavelength source with narrow line width lines (required for low phase noise applications) through spectral broadening is primarily limited by stimulated Brillouin scattering (SBS) which limits the length of non-linear medium and power fed to it. In [7], the HNLF is strained with a specific tension plan to increase the SBS threshold. Moreover, if nonlinear spectral broadening is done with only two lasers [7,11], the repetition rate and bandwidth of the comb achieved are interlinked. Farther wavelength spacing is required for higher comb bandwidth and vice versa.

In the present work, the generated electro-optic frequency combs from two lasers distribute the power to increase the SBS threshold. The spacing between the two lasers can be any integral multiple of the repetition rate providing increased flexibility. The dual carrier electro-optic combs are amplified with an in-house built cascade of Erbium doped fiber (EDF) pre-amplifier and a watt-class Erbium-Ytterbium (Er/Yb) co-doped fiber amplifier and are then propagated through 290 m of HNLF. The use of two lasers generates a pulse profile with a train of narrow pulses (1.4-1.9 ps) whose properties depend on the spectral spacing of lasers and the dc operating point of intensity modulator. This enhances spectral broadening due to SPM and is further verified through simulations. We report a multi-wavelength source with nearly 0.8 W output power with 10-dB flatness extending over 24.6 nm with no missing lines. The repetition rate of the frequency comb can be tuned agilely by changing the microwave frequency of the modulating signal. In this demonstration, it is selected as 25 GHz for compatibility with the DWDM 25 GHz grid. The source is suitable for DWDM based optical communications and spectroscopy. The system can be upgraded to generate locked carriers for orthogonally frequency division multiplexed (OFDM) super-channels by extracting two phase correlated lasers as input pumps, through optical filtering of another electro-optic frequency comb generated by a single laser. This can also be achieved through phase locking the source lasers.

2. Experimental setup

The architecture of the implementation is shown in Fig. 1(a). Two laser sources (line width~100 kHz) are modulated through a cascade of intensity modulator (IM) and phase modulators (PM) driven by a microwave source (25 GHz) to generate the initial frequency combs. RF power was distributed among the modulators to ensure that the phase modulators are driven to their limits, to generate the maximum number of comb lines. The intensity modulator is used to improve the comb flatness. The intensity modulator is driven to $0.5V_{\pi}$ (limited by available

RF power) and is biased at ~0.5 $V_{\pi DC}$. The individual phase modulators are driven to ~0.5 V_π each, corresponding to a total phase modulation amplitude of ~1V_π for the two phase modulators together. The wavelength spacing between the two lasers is chosen to be an integral multiple of the channel spacing (repetition rate) for uniform wavelength spacing of the multi-wavelength source. Power splitters and driver amplifiers drive the modulators to their power handling limit to maximize the number of comb lines. Microwave phase shifters are used to obtain appropriate phase relation between the RF signal applied to the modulators, to produce maximum number of comb lines. This synchronizes the applied RF drive across all modulators. An EDF pre-amplifier compensates the system losses. The generated spectrum for 1.6 nm spacing between the two lasers is shown in Fig. 1(b).

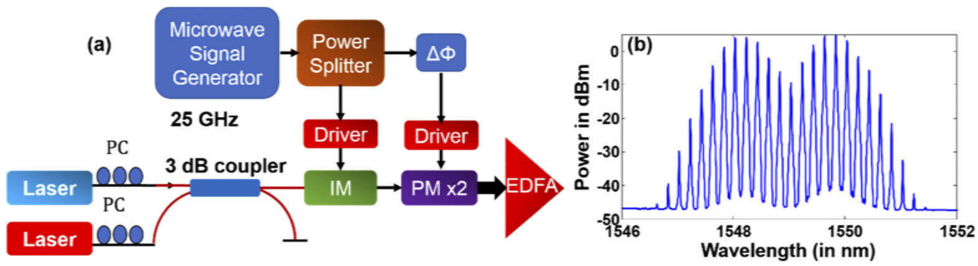

Fig. 1. (a) Frequency Comb generator; IM – Intensity Modulator, PM – Phase Modulator, EDFA – Erbium Doped Fiber Amplifier, PC – Polarization controller, ΔΦ – Electrical Phase Shifter (PM x 2 here denotes a cascade of two-phase modulators, each with its RF drive and phase shifter) and (b) Output spectrum of frequency comb generator with two lasers at 1548.244 nm and 1549.844 nm.

Simulations incorporating transfer functions of modulators are used to visualize the time domain output of the comb generator. With one laser [Fig. 2(a)], the generated pulses have a repetition rate equal to the drive frequency with a FWHM of 16.5 ps. With two lasers, the temporal profile has a substructure with a train of narrow pulses. The repetition rate of this train of pulses is equal to the frequency spacing between the dual carrier lasers. With 1.6 nm spacing [Fig. 2(b)], the substructure repetition rate is 200 GHz with the pulse width (FWHM) of the lobes as 1.9 ps. Figure 2(c) and Fig. 2(d) show the pulse profile for 1.8 nm and 2.0 nm spacing between the lasers where the pulse widths are 1.6 ps and 1.4 ps respectively. Thus, the dual carrier electro-optic combs have pulses which are 8-11 times narrower than the single carrier comb enhancing the SPM based broadening.

The enhancement of peak power in dual laser generated pulses [Figs. 2(b)–2(d)] relative to the single laser case [Fig. 2(a)] can be seen. The generated sub-pulse width reduces with increase in dual laser spacing. However, it also increases the number of sub-pulses, which may reduce their peak powers based on the power distribution among the sub-pulses. This can be seen between Fig. 2(b) and Fig. 2(c), where some of their peak powers reduce with increase in dual laser spacing due to two of the sub-pulses having almost the same peak power. In the case of Fig. 2(d), due to non-uniform distribution of power among the sub-pulses, some of their peak powers have increased. The increase in peak power and the burst of narrow sub-pulses generated by dual laser system allow enhanced SPM effects in the nonlinear spectral broadening stage (Fig. 3).

The EDF pre-amplifier output (~40 mW) is further power scaled by a high power Er/Yb amplifier to nearly 1 watt. The input isolator of Er/Yb amplifier protects the components preceding the amplifier. The output isolator of Er/Yb amplifier prevents backward power from entering the gain fiber. The amplified seed propagates through 290 m of HNLF with a zero-dispersion wavelength of 1550 nm to achieve non-linear spectral broadening.

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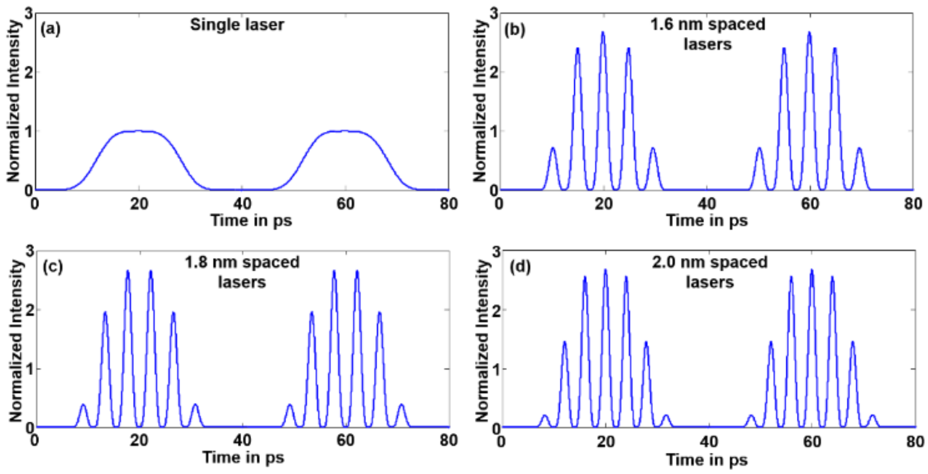

Fig. 2. Simulated temporal profile after modulators for (a) one laser. Simulated temporal profile after modulators with the dual lasers spaced in wavelength by (b) 1.6 nm, (c) 1.8 nm and (d) 2 nm.

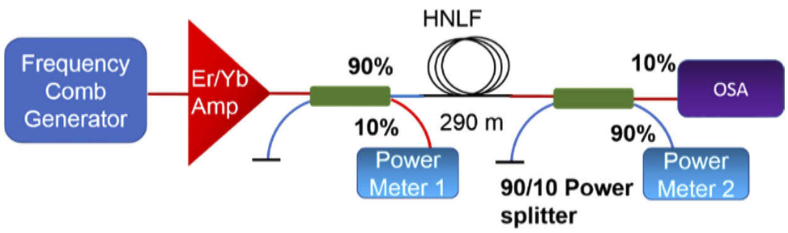

Fig. 3. Non-Linear Spectral broadening of the Frequency Comb; Er/Yb Amp – Erbium-Ytterbium Co-doped Fiber Amplifier, HNLF – Highly Non-Linear Fiber, OSA- Optical Spectrum Analyser.

2.1. Stimulated Brillouin scattering limitations on power scaling

Narrow linewidth (~100 kHz) carriers are essential for low phase noise applications such as DWDM systems. To increase the number of carriers in a narrow band multiwavelength source through nonlinear spectral broadening, power scaling is essential. However, power scaling of narrow linewidth laser sources is limited by SBS. For example, the HNLF utilized has a typical value of 18 W-m for the product of SBS threshold (W) and effective length (m). The nonlinear parameter of the HNLF (γ) is 11.3/W-km. The effective length L_{eff} is given by

$$L_{eff} = \left(\frac{1 - e^{-\alpha L}}{\alpha}\right) \tag{1}$$

Here L is the length of HNLF and α is the attenuation constant. The attenuation constant for the HNLF is 0.163/km. This leads to an effective length of ~ 283 m resulting in an SBS threshold of ~64 mW for a single laser. By distributing the power across carriers in a comb, the SBS threshold power can be increased by reducing the peak spectral power within a Brillouin bandwidth. When the separation between comb lines is greater than Brillouin bandwidth (usually few tens of MHz), the stokes wave for each comb line evolves independently. Due to variation in power across the comb spectrum, the carrier with the highest power determines the SBS threshold.

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The SBS threshold for a comb can be estimated from the comb spectrum. Assuming flat gain from the fiber amplifier over the comb bandwidth, power scaling would preserve the ratio of powers across the comb. The factor by which the strongest comb line should be power scaled to reach the SBS threshold power of a single laser (~64 mW) is calculated. The power of the whole comb is risen by this scale factor to give the estimate of the SBS threshold of the comb. When comb is generated from only one laser, the $SBS_{\text{threshold estimate}}$ is ~262 mW. For the combs generated by dual lasers with 1.6 nm spacing between the lasers, the $SBS_{\text{threshold estimate}}$ is ~432 mW, the increase attributed to distribution of power across a wider band. Though, $SBS_{\text{threshold estimate}}$ of dual laser seeded comb is expected to be twice the $SBS_{\text{threshold estimate}}$ for single laser seeded comb, it is only ~1.65 times the $SBS_{\text{threshold estimate}}$ of the single laser seeded EOM comb. This is due to asymmetry in the spectral powers between the strongest lines generated by each comb [~0.9 dB in the case of Fig. 1(b)]. As a result, in the dual laser seeded comb, the peak spectral power did not reduce by 3 dB over the single laser seeded comb case. The small asymmetry in spectral powers is attributed to a variety of factors including a slight difference in source laser powers, a small asymmetry in the combining ratio of the 3-dB coupler and a small difference in alignment of laser polarization (achieved through polarization controllers) to the modulators. However, these estimates are valid only under the assumption of no spectral broadening in the fiber which is not the case in the present experiments.

In the presence of spectral broadening, these calculations are gross underestimations. Spectral broadening in HNLF generates new carriers, thus redistributing the power among more lines resulting in increased SBS threshold. The SPM based spectral broadening at a given power strongly depends on the pulse profile. The relatively wide pulses, with low peak power generated by single laser comb [Fig. 2(a)] cause inferior spectral broadening in comparison to the dual laser combs which generate a burst of narrow sub-pulses, with higher peak power [Fig. 2(b) to Fig. 2(d)]. This allows the dual laser comb system to be power scaled to much higher powers than the single laser comb.

Often, SBS threshold is measured as the input power where the reflected power attains a fraction of input power. However, this definition of SBS threshold is not always suitable. Particularly, in fiber amplifier-based systems, the backward power (SBS stokes wave) entering the amplifier also increases in strength and causes catastrophic destruction (of the amplifier and preceding components) whenever pulses of high peak power occur. For safe operation of the system, the occurrence of pulses is taken as indication of SBS initiation [14] and the operating power is kept below the regime where pulses occur.

Though the output isolator of Er/Yb amplifier blocks the continuous wave stokes power, sharp pulses are not attenuated sufficiently. They subsequently attain gain in the Er/Yb fiber amplifier leading to catastrophic destruction. The power limit for safe operation is determined by observing temporal oscillations detected from a photodiode upon which backward light is incident from the coupler between amplifier and HNLF. The temperature of the output isolator in Er/Yb amplifier acts as an indicator of the average backward power and is monitored with an infrared camera. In the present system [Fig. 1(a) and Fig. 3], when only one laser is used, Er/Yb amplifier power scaling is limited to ~640 mW. This limits the maximum output power (after HNLF) to ~480 mW (due to propagation and splice losses). At this power level, sharp pulses are noticed in the oscilloscope indicating the limit of safe regime of operation. The temperature of the Er/Yb amplifier's output isolator increased to ~33 °C, indicating presence of significant average backward power. The spectrum measured in this case is shown in Fig. 4 and has 12 lines in 10 dB bandwidth. In the dual laser configuration, the Er/Yb amplifier power was increased to ~1.2 W. The maximum power in this case is limited by the amplifier used and not by SBS. No pulses are observed on the oscilloscope and the temperature of the output isolator is below 30 °C, indicating that the backward power is insignificant. The spectra for dual laser configuration are discussed in the results section.

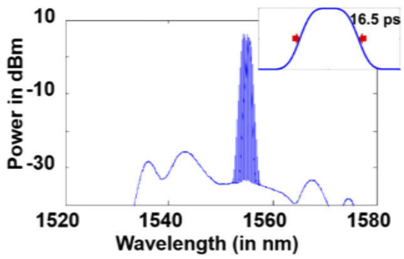

Fig. 4. Observed spectral broadening with single laser (simulated pulse envelope shown on top right corner).

3. Results

The evolution of the spectrum at the output of HNLF as the Er/Yb amplifier gain is increased is shown in Fig. 5 for two lasers spaced by 1.6 nm (1549.844 nm, 1551.444 nm). Before entering the nonlinear medium, the spectrum consists of 23 comb lines above the noise floor, of which 12 are within 10 dB from the peak (2.2 nm 10-dB bandwidth) and the total bandwidth of the comb (23 lines) is 4.4 nm. The maximum output power in this case is ~ 0.8 W [Fig. 6(a)], which is limited by the fiber amplifier. With the lasers spaced by 1.6 nm, there are 85 lines (16.8 nm or 2.096 THz) in 5 dB from the peak, 113 (22.4 nm or 2.795 THz) lines in 10 dB from the peak and 143 lines (28.4 nm or 3.544 THz) in 20 dB from the peak [Fig. 6(a)]. With the spacing between lasers increased to 1.8 nm, there are 95 lines (18.8 nm or 2.346 THz) in 5 dB from the peak, 124 lines (24.6 nm or 3.069 THz) in 10 dB from the peak and 157 lines (31.2 nm or 3.9 THz) in 20 dB from the peak [Fig. 6(b)].

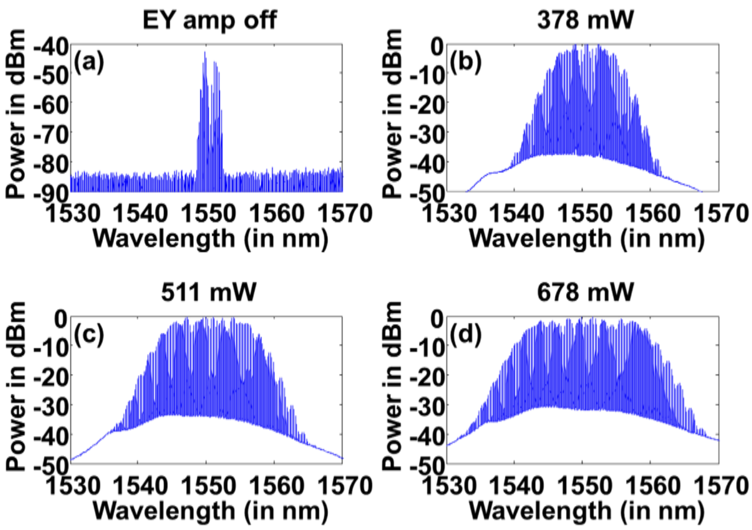

Fig. 5. Multi-wavelength source evolution with (a) power amplifier off; output power of (b)378 mW; (c) 511 mW; (d) 678 mW; input lasers at 1549.844 nm and 1551.444 nm.

When the dual carrier spacing was further increased to 2 nm [15], there are 103 lines (20.4 nm or 2.545 THz) in 5 dB from the peak, 137 lines (27.2 nm or 3.394 THz) in 10 dB from the peak and 174 lines (34.6 nm or 4.317 THz) in 20 dB from the peak [Fig. 6(c)]. But the 10-dB bandwidth has two missing lines in the spectrum. Further increase in the spacing between the lasers is

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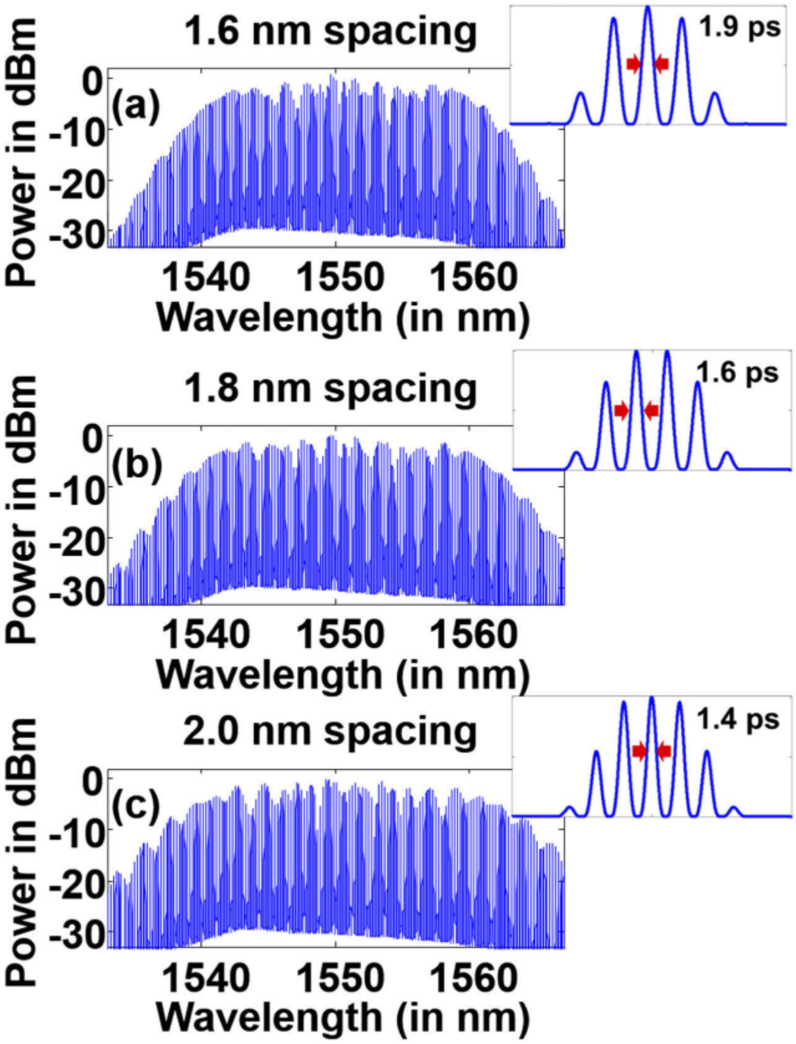

Fig. 6. Measured OSA Spectrum with two lasers at (a) 1549.844 nm, 1551.444 nm with output power 833 mW; (b) 1549.844 nm, 1551.644 nm with output power 811 mW; (c) 1549.844 nm, 1551.844 nm with output power 878 mW. Simulated pulse envelope entering nonlinear medium in each case is shown on upper right corner.

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found to result in more missing lines. This is due to the increase in spectral gaps between the independent electro-optic combs. Though spectral broadening mostly fills the gaps, some lines do not acquire enough power, to be within the desired power band from the peak (for example, 10 dB or 20 dB bandwidth). As a result, the spectrum with the 1.8 nm spacing [Fig. 6(b)] is the widest spectrum with no discontinuity in 10 dB bandwidth. With variation in spacing between the two lasers, the pulse profile changes as shown (MATLAB visualization) in the upper right corner of each spectrum. The narrow pulses enhance the SPM effects.

The enhanced broadening in HNLF is primarily due to SPM and is explained with simulations incorporating the transfer functions of intensity modulator and phase modulators along with SPM effect. The behavior of intensity and phase modulators is incorporated using Eqs. (2) and (3) as follows.

$$E_{IM} = E_{in} * (1 + \cos(\pi * ((\frac{V_{DC}}{V_{\pi DC}}) + (\frac{V_{RF\ IM}}{V_{\pi\ IM}})\cos(\omega_{RF} t)))) \tag{2}$$

$$E_{PM} = E_{in} * e^{i*(\cos(\pi*(\frac{V_{RF\ PM}}{V_{\pi PM}})\cos(\omega_{RF} t)))} \tag{3}$$

Here, E_{in} is the input optical field. V_{DC} is the dc bias of the intensity modulator. $V_{RF\ IM}$ and $V_{RF\ PM}$ are the RF drive voltages to the intensity and phase modulators, respectively. ω_{RF} is the angular frequency of the RF drive. $V_{\pi DC}$ is the DC half wave voltage of the intensity modulator. $V_{\pi\ IM}$ and $V_{\pi\ PM}$ are the RF half wave voltages of the intensity and phase modulators.

The electro-optic comb field E_{EOcomb} is simulated by cascading the transfer function of one intensity modulator and two-phase modulators.

$$E_{EOcomb} = E_{in} * (\frac{E_{IM}}{E_{in}}) * (\frac{E_{PM}}{E_{in}}) * (\frac{E_{PM}}{E_{in}}) \tag{4}$$

The modulator parameters used are based on experimental parameters. The DC bias of the intensity modulator is set to 0.5 $V_{\pi DC}$ and its RF drive amplitude is 0.5 $V_{\pi\ IM}$. The individual phase modulators are driven to ~0.5 $V_{\pi\ PM}$ each, corresponding to a total phase modulation amplitude of ~1$V_{\pi\ PM}$ for the two phase modulators together. Timing synchronization between modulators (achieved through phase shifters in the experiment) is assumed and no additional RF phase is considered for the drive signals of the phase modulators. The amplified comb output field $E_{Amp\ comb}$ is used in the following equation to simulate SPM based broadening in HNLF [16].

$$E_{out} = E_{Amp\ comb} * e^{(-0.5*\alpha z)} * e^{(ik\gamma z_{eff}|E_{Amp\ comb}|^2)} \tag{5}$$

Here α (0.163/km) is the attenuation constant, γ (11.3/W-km) is the nonlinear parameter of the HNLF and z (290 m) is the length of the HNLF. z_{eff} (283 m) is the effective length for fiber. The dispersion of HNLF is negligible and is ignored (zero dispersion wavelength is 1550 nm with a dispersion slope of 0.017 ps/nm^2-km). A correction factor, 'k' is used to account for the deviation of experimental parameters from the specifications and splice and coupler losses. The value of k is obtained by optimizing its value in the simulation to get the spectral broadening to closely match the experimental results. The value of k (0.44) obtained in the case where the two lasers are spaced by 1.6 nm is used for other cases (1.8 nm and 2.0 nm spacing) and the simulations in the other cases are also very close to the experimental bandwidths. The simulation result for 1.6 nm spacing is shown in Fig. 7 which is in good agreement with the experimental result [Fig. 6(a)]. The number of lines in 10 dB bandwidth from the peak are 109 and is in close agreement to the experimental result of 113. For 1.8 nm spacing, simulations predict 122 lines in 10 dB bandwidth against the experimental value of 124. Similarly, for 2 nm spacing, the simulation predicts 142 lines in 10 dB bandwidth which is very close to the experimental value of 137. These simulations show that the enhanced spectral broadening is primarily due to the modified temporal profile with a substructure of narrow pulses that enhance SPM effects.

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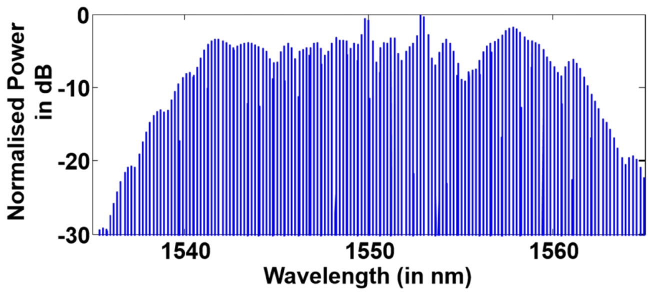

Fig. 7. Simulated spectrum of multi-wavelength source with lasers at 1549.844 nm and 1551.444 nm (spectrum normalized to peak).

As the broadening is mainly due to SPM, the resultant spectrum is highly stable. Each of the lines that are in the spectra (Fig. 6) can be individually extracted by demultiplexers. The two lasers used here are independent of each other and thus will have uncorrelated drifts. However, the extent of drift between two spectrally overlapping lines in this system is of the order of only 120 MHz (24 fm) [17]. Such small drifts cannot be observed by optical spectrum analyzer (resolution 0.02 nm). As the spacing between adjacent lines is several orders higher (25 GHz) than the range of drift (120 MHz), the multiwavelength source implemented can be reliably used for high bandwidth DWDM communications. The measured spectra are stable over fifteen minutes of operation to 0.2 dB which is within the accuracy limit of OSA. Experimental measurements of the temporal waveforms of the dual laser generated pulses and the broadened spectrum are interesting to pursue for a more detailed understanding of the influence of sub-pulses on spectral broadening and is something we are looking at in future.

4. Summary and conclusions

We have demonstrated a multi-wavelength source spanning the entire C-band with 124 lines within 10 dB flatness constituting a bandwidth of 3.07 THz. Dual carrier combs simultaneously enhance SPM based broadening and increase the SBS threshold. The dual carrier combs have narrow pulses that are compressed by 8-11 times over the single laser comb enhancing the SPM effects. The SPM enhancement by dual carrier combs is further verified through simulations. The source can serve as a versatile DWDM carrier source and can be upgraded for OFDM super channels. The use of electro-optic combs allows the carrier spacing to be tunable.

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Disclosures

The authors declare no conflicts of interest.

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