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Tailored optical feedback for bandwidth scaling and spectral equalization of high repetition rate electro-optic frequency combs

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Abstract: Direct bandwidth scaling of high-repetition-rate electro-optic (EO) frequency combs is limited by the power handling capability of modulators used. Significant bandwidth can be achieved by using nonlinear spectral broadening of a single laser comb, but current techniques for this have limited spectral flatness. Using dual or multiple laser combs enable enhanced nonlinear broadening with equalized spectra. However, if the lasers are uncorrelated, coherence is not preserved and only a multi-wavelength source is obtained. If the multiple lasers are derived from a single initial comb, coherence is preserved after spectral broadening. One way of achieving this is by direct filtering and amplification of a few comb lines from an initial EO comb and using it to coherently pump a cascade of nonlinear fibers. Alternatively, optical feedback can be used to feed a fraction of the entire output back. While the former technique requires additional components, the latter suffers from limited bandwidth scaling and degraded signal-to-noise ratio. We have discovered that by filtering the feedback to only consist of a few, suitable comb lines, a coherent, equalized, bandwidth scaled comb is obtained. We demonstrate a 25 GHz repetition-rate frequency comb in the C-band with ~27 dBm power and 100 usable sub-carriers.

1. Introduction

An optical frequency comb (OFC) is a broadband optical source consisting of a series of evenly spaced discrete frequency components having a coherent and stable phase relationship. Generation of OFCs can be achieved using different technologies. Mode locked lasers are widely used for OFCs with low repetition rates [1]. At high repetition rates, these systems become unstable resulting in increased design and operational complexity. Kerr comb generation in micro-resonators has been demonstrated using various technology platforms and results in the generation of frequency combs with large free spectral range (FSR) and large mode spacing with typically fixed repetition rates and limited center frequency tuneability. High repetition rate OFCs with independent tuning of the repetition rate and optical center frequency are desirable for applications in radio frequency (RF) photonics [2], optical arbitrary waveform generation (OAWG) [3], ultra-short pulse generation [4] and optical communications [5]. An approach to generate such tunable, high repetition rate combs is by strong electro-optic phase modulation. This is achieved by applying strong sinusoidal phase modulation to a continuous wave (cw) laser [6]. But, the resulting OFCs have poor spectral flatness, with significant line-to-line amplitude variations and limited number of comb lines. The spectral flatness can be improved by using cascaded intensity and phase modulators driven by tailored radio frequency waveforms [7], and bandwidth can be scaled by using multiple phase modulators (PMs). A cascade of PMs would still result in only a linear increase in the number of spectral lines with further scaling in bandwidth restricted by the RF power handling capability of modulators used. Cascaded four wave mixing (FWM) and self-phase modulation (SPM) assisted nonlinear spectral broadening provides an

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effective alternative [8,9]. This is commonly achieved by using cascaded stages of single mode fiber (SMF) and highly nonlinear fiber (HNLF) [9,10]. SMF is used to compensate the dispersion induced chirp, forming pulses with high peak powers. Instead of SMF to compensate dispersion, a pulse shaper can be utilized as well [Fig. 1(a)]. These tailored high peak power optical pulses upon propagating through HNLF cause significant improvement in OFC bandwidth. But this technique results in poor spectral flatness around the central region. Additionally, favorable time domain features conducive to spectral broadening in a variety of configurations can be introduced by employing adaptive spectral phase optimization techniques [11] but the system requires complex iterative algorithms and the resulting OFC has reduced spectral flatness with sharp SPM nulls. Using multiple pump lasers [12–14] provides enhanced bandwidth scaling without the need for additional spectral shaping [Fig. 1(b)]. However, this results in a multiwavelength source and not a frequency comb since the different sets of spectral lines are incoherent with respect to each other. The lack of coherence across the spectrum makes this source unattractive for many comb applications. Frequency locking the multiple pump lasers [15] improves temporal coherence, but range of locking is limited with a significant increase in system and operational complexity.

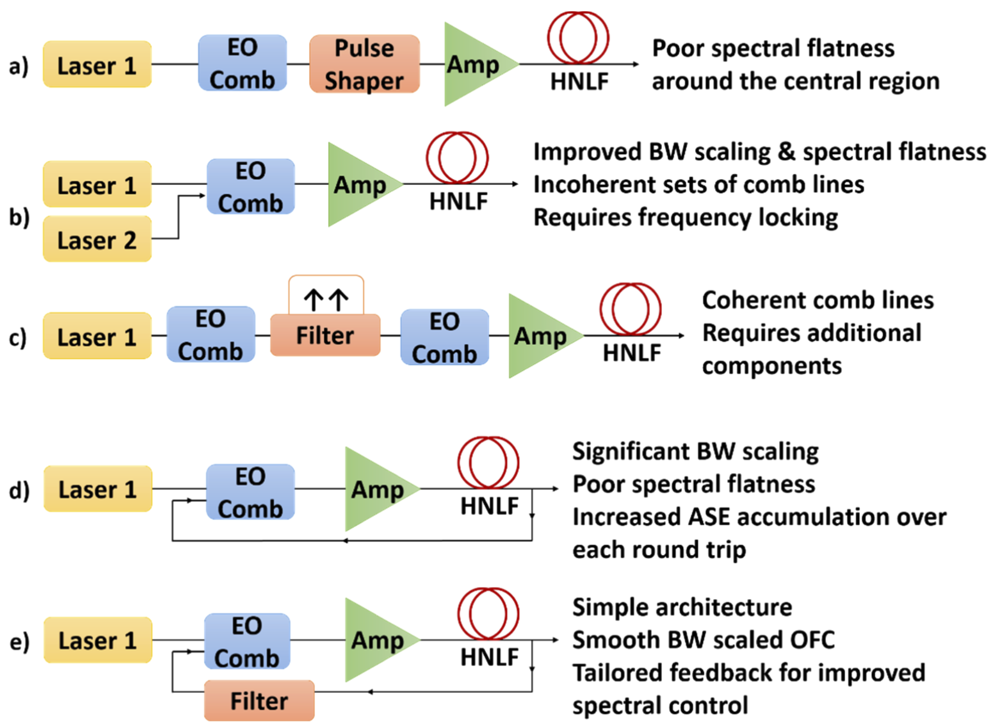

Fig. 1. (a to d) Nonlinear bandwidth scaling techniques of OFC along with their pros and cons. (e) Proposed schematic using filtered feedback with select lines from the output.

A simpler way to generate phase locked multiple pump lasers is to derive them from a frequency comb itself [Fig. 1(c)]. By selecting two lines from the output of the modulator, the behavior of a dual laser drive along with coherence preservation of lines can be implemented [16]. But this technique requires additional modulators and amplifiers owing to the low powers of the extracted comb lines and hence reduced OSNR of the newly generated lines. Another strategy to mimic this effect is the use of an optical feedback. Architectures with recirculating frequency shifters or optical feedback loops have been previously demonstrated [17–19]. With an all-pass feedback architecture after the HNLF stage [Fig. 1(d)] OFC scaling is achieved by tuning the percentage

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of feedback power. But the spectral profile is uneven and dominated by the strong central lines fed back after every round trip. Further, OSNR degradation owing to amplified spontaneous emission (ASE) buildup is significant. We identified that for a smooth spectral profile, it was necessary to filter the feedback [Fig. 1(e)] to exclude the dominant central lines from the output.

In this letter, we propose a simple architecture to obtain a smooth, bandwidth scaled OFC where we enhance the nonlinear spectral broadening of electro-optic comb in HNLF and the resultant spectral flatness through tailored optical feedback. The use of feedback enhances FWM. By tailoring the pass band of filter in the feedback path, we achieved enhanced spectral flatness with significant improvement in bandwidth of OFC.

2. Experimental setup

The architecture for OFC generation using a cw laser source as pump is shown in Fig. 2. Fiber amplifier in the forward path provides the necessary power for scaling the frequency comb in HNLF. A narrow linewidth (~100 kHz) cw laser source operating at 1550 nm is fed into a lithium niobate cascaded intensity and phase modulator (IM-PM) based electro-optic (EO) comb generator through a polarization controller (PC). PC is used to align the polarization of input laser to the axis of modulator to obtain the best possible modulation efficiency. The IM DC bias is adjusted for maximum flatness. PM is driven near its RF power handling limit and phase shifters are used for maintaining proper phase relation of the microwave driving signal between the cascaded modulators to maximize the number of comb lines. The narrow linewidth input laser has 15 dBm power at 1550 nm.

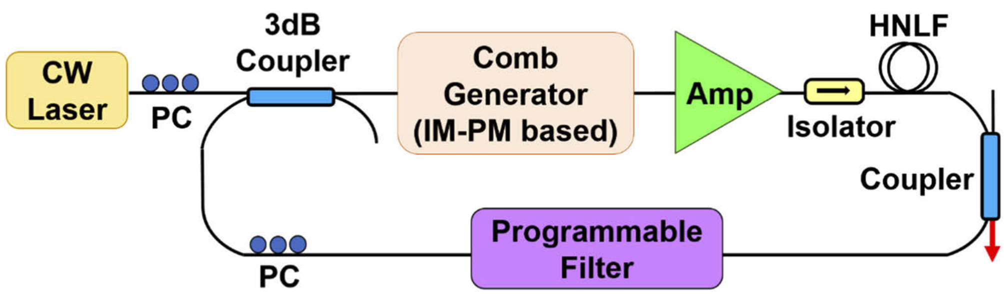

Fig. 2. Schematic of the 25 GHz spaced frequency comb generator centered around 1550 nm with tailored optical feedback. CW - continuous wave, PC - polarization controller, IM - intensity modulator, PM - phase modulator, Amp – amplifier, HNLF - highly nonlinear fiber.

The output of EO comb generator measured using an optical spectrum analyzer (OSA) with 0.02 nm resolution has 9 lines within 20 dB bandwidth (BW) and 7 lines within 10 dB BW centered around 1550 nm as shown in Fig. 3. The repetition rate of the frequency comb is tunable and is selected as 25 GHz for this experiment to be compatible with the DWDM grid (as a harmonic multiple). The OFC from the comb generator is bandwidth scaled by cascaded FWM using HNLF. Since the power in the initial comb lines is too low to have discernible nonlinear effects, an in-house built Erbium-Ytterbium co-doped fiber amplifier (EYDFA) is used to amplify the EO frequency comb. The EYDFA uses a 976 nm semiconductor diode as a pump and 5 m of Erbium-Ytterbium co-doped fiber as the gain medium to provide up to 30 dBm output power. The amplified EO comb is used to pump nearly 300 m of HNLF with a zero-dispersion wavelength around 1553 nm, effective area ~ 11.8 μm^2 at 1550 nm and nonlinear coefficient ~ 11 (W-km)$^{-1}$. An isolator is used to protect the EYDFA from any backward propagating light around 1550 nm.

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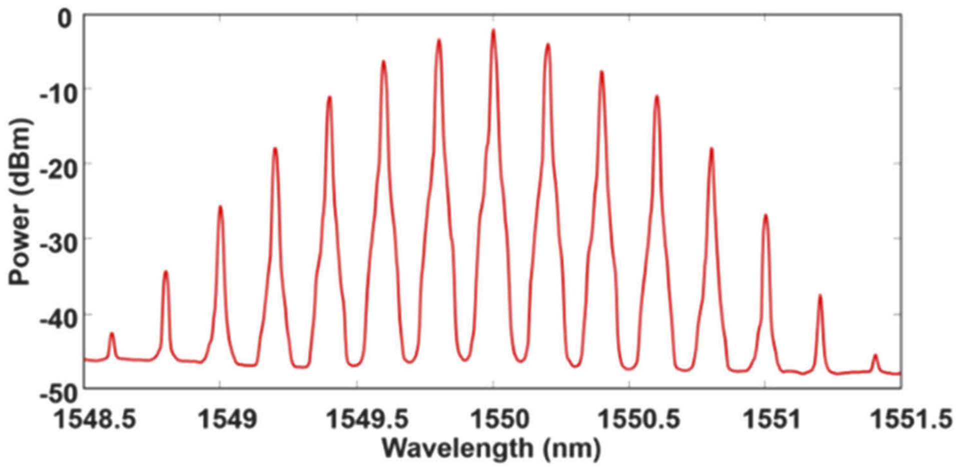

Fig. 3. Output spectrum of the 25 GHz spaced electro-optic modulator-based comb generator.

3. Results

With only the forward path i.e., in the absence of any feedback, a small increase in the number of sub-carriers is observed. The OFC obtained has 16 lines within 20 dB BW and ~25 dBm of optical power concentrated around the central wavelength region due to which limited bandwidth scaling was achieved. A simple addition of feedback path from output to the input of the EO modulator through a coupler results in a BW scaled frequency comb with poor spectral profile as shown in Fig. 4(a). By using a programmable filter in the feedback path, we were able to control the bandwidth and number of comb lines fed back into the modulator.

In this experiment, a Fourier pulse shaper (Finisar wave-shaper 1000S) with a filter bandwidth resolution of 10 GHz, operating in the C-band was used to selectively carve out the desired comb lines as feedback. The amplitude masks (with no phase control) transmit only the selected comb lines with no additional attenuation. While increased power in the feedback path yields a broader OFC, the percentage of feedback is limited by the power handling capability of the programmable filter used. Thus, an optimum value that yields the best result is chosen. A polarization controller (PC) is used to align the polarization of feedback signal to that of the axis of modulator.

Figure 4(b) shows the output spectrum when the filter is programmed to transmit only the comb lines while suppressing the ASE noise between the lines. There is a remarkable improvement in the background noise and total number of usable comb lines, but the OFC has a poor spectral profile especially around the central region where the total power is concentrated. We predicted that by tailoring the feedback to include only a subset of the comb lines, we would be able to obtain a smooth OFC with improved distribution of power around the central region. Such an OFC is both spectrally flat and BW scaled easily. The choice of wavelengths fed back, owing to their relative spectral position and power distribution strongly influences the spectral flatness.

When the strong central lines are fed back, new comb lines generated by them would be close to the comb lines generated by the external pump laser. As a result, a major fraction of the spectral power would still be concentrated around the central peak, leading to a marginal gain in bandwidth and poor flatness. In contrast, if only the lines away from center are fed back, they would significantly increase the generation of comb lines away from those generated by the external laser source. This encourages distribution of spectral power away from the center, leading to broader comb bandwidths. To emulate a coherent multiple pump driven OFC, two

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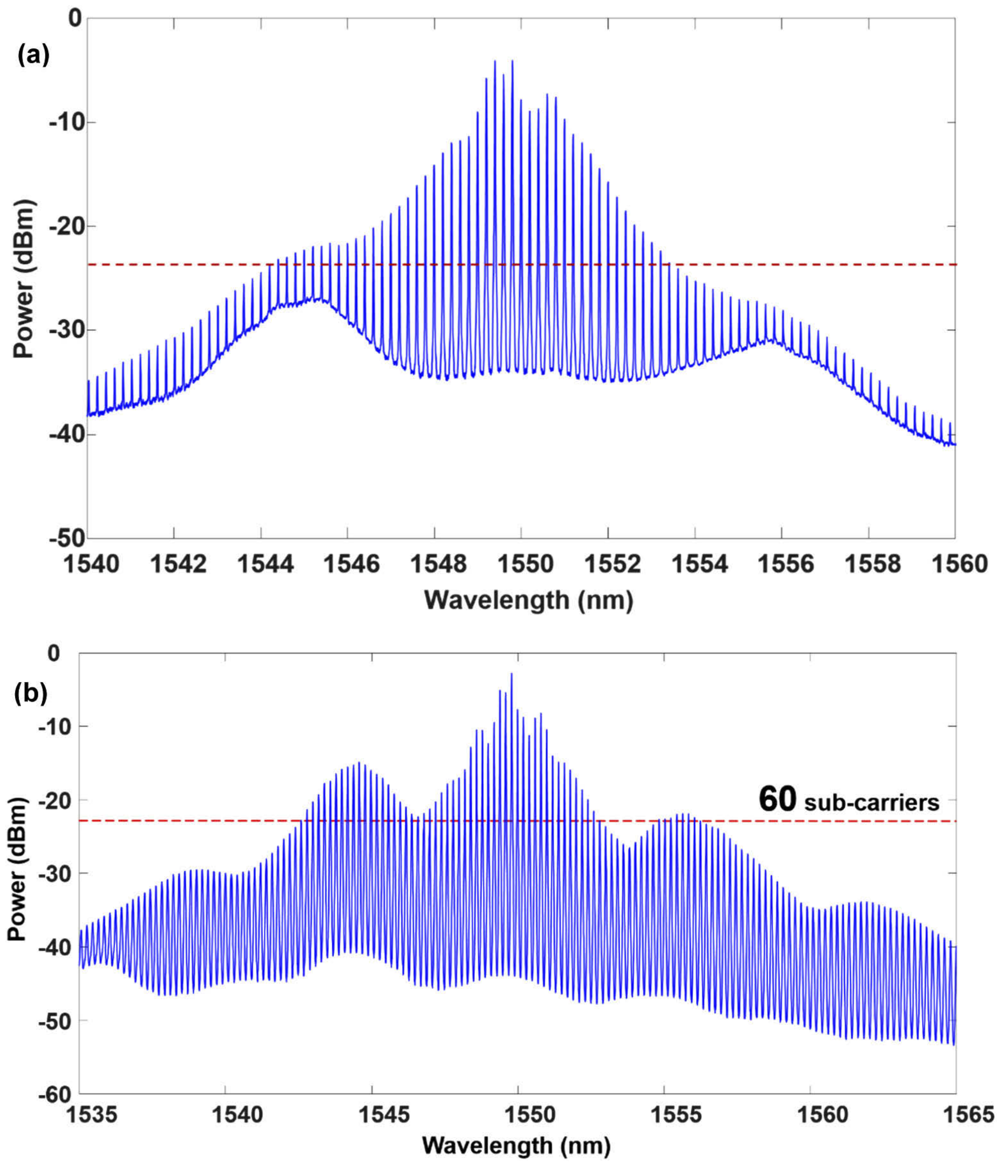

Fig. 4. The output spectrum obtained when (a) No filter is used in the feedback path, (b) Programmable filter is used to transmit all the comb lines in C-band.

lines are initially fed back. A symmetric feedback profile of one line on either side ('-' denoting lines to the left and '+' denoting lines to the right) of the central wavelength was chosen.

The characteristics of OFC, viz. the envelope and bandwidth vary significantly depending on the feedback lines chosen. When the central line or lines around the central wavelength is fed back, the OFC envelope is nearly triangular with limited bandwidth scaling as shown in Fig. 5(a). The slope of the comb is quasi-linear in log scale. As the lines away from the center are fed back, for example in Fig. 5(b) with 7th line on either side, the OFC has a smoother shape with much wider bandwidth and greater number of sub-carriers. By feeding back lines well beyond the central 1550 nm, a peaky spectral profile with bunches were obtained as shown in Fig. 5(c). Selecting lines further away resulted in discontinuous frequency comb with missing sub-carriers,

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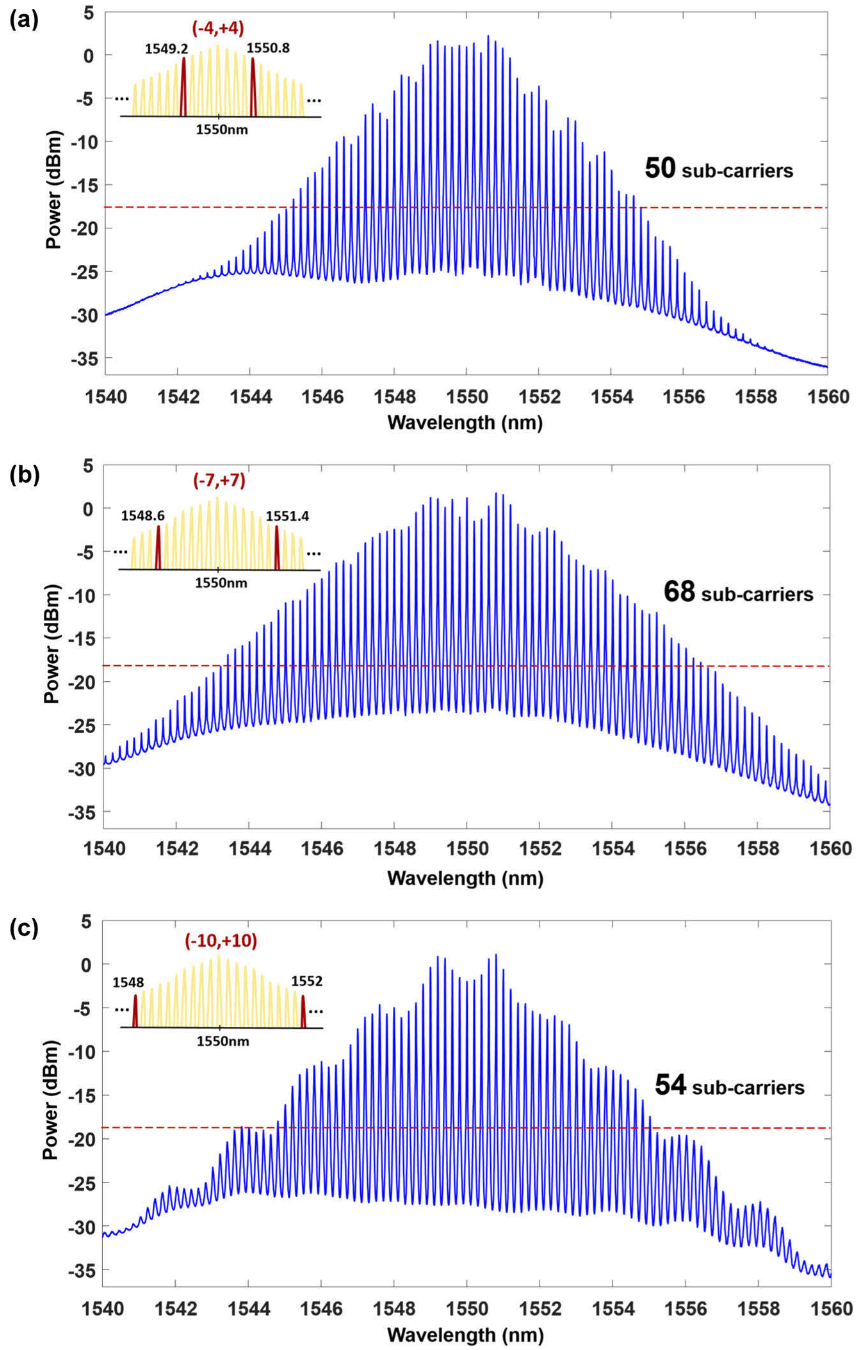

Fig. 5. The output spectrum obtained when (a) 4^{th} line on either side, (b) 7^{th} line on either side and (c) 10^{th} line on either side of the central wavelength were used as feedback. Inset represents the respective filter action used in each case.

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owing to significant spectral gaps between the new comb lines generated from fed back lasers and the comb lines generated from the external laser. The output power of the OFC is dominated by the presence of amplifier and remains largely same for different feedback lines chosen. However, when weak lines were fed back, we observed an increase in noise level and degraded SNR around the spectral edges. With this investigation, we anticipated that by selecting a combination of feedback lines (or super-modes) with suitable power and spacing, improved spectral smoothness and bandwidth scaling could be achieved.

Different super-mode emulating shapes were investigated. If the super-modes with lines around the central wavelength were fed back, an OFC having a peaky structure in the central region was obtained. Feeding back super modes spaced far away from the center did not cause a significant change in the number of usable carriers in OFC. Additionally, if the individual lines in the super-modes were spaced far away from each other, frequency comb bunches were formed. Thus, a super-mode with a combination of lines suitably spaced from the center and from each other results in a broad, equalized, and smooth OFC. Through iterative optimization process, a suitable tailored feedback was chosen.

Several combinations of lines yield improved results. Figure 6 represents one such optimal case of feeding back a super-mode with a group of comb lines in clusters i.e., with 5th, 6th, 7th, and 8th lines on either side of the central wavelength. The OFC in Fig. 6 has an enhanced bandwidth and smooth spectral profile with ~ 27 dBm of power and 100 lines within 20 dB BW and 64 lines in 10 dB BW from the peak. Owing to the lack of dominant lines across the spectrum in Fig. 6, optimal SBS suppression is achieved, and the output power of the broadband OFC is amplifier limited. The effectiveness of the proposed architecture can be identified by comparing the initial EO comb used (Fig. 3) and the optimized OFC with tailored feedback shown in Fig. 6. A ten-fold improvement in the number of subcarriers within 20 dB BW is demonstrated in this work. We anticipate that the use of an EO comb similar to [19] would enable substantially higher number of lines in our system. The flatness of the OFC can be further improved by using an equalizing filter at the output as in [19]. However, this will introduce additional losses and increase the system cost and complexity.

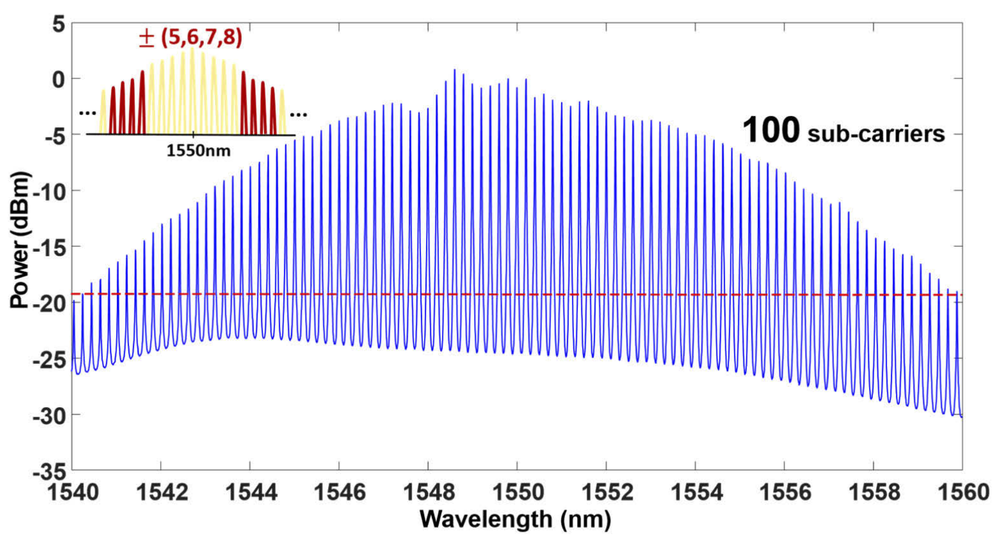

Fig. 6. Output spectrum with tailored line group containing 5th, 6th, 7th and 8^{h} lines on either side of central wavelength fed back.

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In the current work, the tailoring of the optical feedback was done with the help of a Fourier pulse shaper-based programmable filter. This was driven primarily by the need to optimize the feedback required to get the best comb. Once such an optimal profile is identified, such as the one shown in Fig. 6, the feedback path can be substantially simplified by using a demultiplexer-multiplexer pair instead of a programmable filter as shown in Fig. 7. This implementation is advantageous from a practical and engineering point of view.

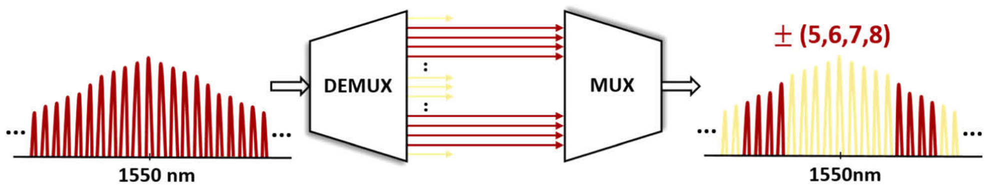

Fig. 7. Use of a simple demultiplexer-multiplexer combination in the feedback path for tailored feedback of line group containing 5th, 6th, 7th and 8^{h} lines on either side of central wavelength.

4. Summary and conclusions

We have demonstrated a simple and effective technique for bandwidth scaling and spectral equalization of single cw laser pumped electro-optic frequency comb in HNLF through tailored optical feedback. We have also discussed the effect of feedback tailoring on the shape of nonlinearly broadened frequency combs. With this understanding, we have optimized the nature of super-modes required to yield a smooth, broadband OFC with no missing lines. The optimal result is illustrated with a 25 GHz frequency comb spanning 2.5 THz bandwidth in the C-band with ~27 dBm power and 100 usable sub-carriers. With the tailored feedback, we have achieved a ten-fold increment in the number of phase-locked sub-carriers as compared to that of the initial electro-optic comb. The OFC generated using feedback mechanism is similar in nature to a Kerr comb, however greater control is being exercised with spectral filtering in the feedback. This benefit is not applicable to Kerr combs currently. Future work would involve looking at this novel comb in the time domain to better understand the dynamics of the system.

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Disclosures

The authors declare no conflicts of interest.

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