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Characterization of a multifunctional active demultiplexer for optical frequency combs

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ABSTRACT

We report on a multifunctional active demultiplexer for optical frequency combs. The proposed technique, based on injection locking, combines the functionality of a tunable demultiplexer, gain equalizer and an optical amplifier, all in one device. Validation of the concept is experimentally demonstrated through simultaneous demultiplexing and amplification of combs with various free spectral ranges (2.5 to 15 GHz), achieving an adjacent channel suppression ratio $>$ 35 dB and an output power of 7.5 dBm. The functionality of the demultiplexer is extended to that of a gain equalizer, by filtering comb tones with powers 10 dB below the spectral peak, whilst maintaining a suppression ratio $>$ 30 dB and a constant output power. This feature increases the number of comb lines suited for data modulation (i.e. usable lines), by a factor of ~1.7. Finally, we test the stability of such a demultiplexer, by measuring the frequency drift, beat tone power variations and phase correlation between demultiplexed tones.

1. Introduction

Over the last decade, extensive use of various bandwidth-intensive applications has led to an unprecedented increase in the global data traffic. As the demand for bandwidth grows, optimum utilization of the legacy optical fiber infrastructure is essential. A possible solution to maximize the use of the existing network resources, is the employment of flexible superchannel based optical networks [1]. Spectrally efficient multicarrier transmission techniques, such as Nyquist wavelength division multiplexing (NWDM) [2] and coherent optical orthogonal frequency division multiplexing (CO-OFDM) [3], have been investigated to realize multi-terabit flexible superchannels. In such networks, capacity increase is achieved by using densely packed channels. The channel spacing could be reduced to 6.25 GHz or even lower, thus imposing a strict and very challenging requirement on the frequency stability of the laser transmitter [4]. An attractive solution, allowing to meet these demands, entails the use of an optical frequency comb (OFC), which provides multiple carriers that are intrinsically equidistant in frequency. The precise free spectral range (FSR) of a comb enables the reduction of the size of guard bands between data channels, thereby significantly enhancing the spectral efficiency of a network. However, one of the main challenges in employing OFCs in such ultra-dense WDM networks, is the complexity involved in demultiplexing closely spaced comb lines, prior to data modulation. Conventionally, WDM systems employ demultiplexers based on arrayed waveguide gratings (AWGs) and wavelength selective switches (WSSs), as illustrated in Fig. 1(a). However, these devices do not possess sufficient bandwidth resolution to separate comb lines with FSRs $<$ 12.5 GHz [5]. In addition, they introduce a large insertion loss that is typically compensated using an optical amplifier, which in turn adds noise. Therefore, an effective demultiplexing technique is required to overcome these drawbacks. One such technique is based on optical injection locking (OIL) [6]. This method allows the selection of closely spaced comb tones, without insertion loss and any constraints regarding asymmetrical channel spacing (multiples of the FSR) [7]. In previous work, we reported on the performance of the demultiplexer as a function of the injection parameters [8].

In this article, we present a comprehensive experimental characterization of the multifunctional operation of the active demultiplexer, including the FSR tunability, ultra-low noise amplification and gain equalization. Firstly, the demultiplexing operation is illustrated, by successfully selecting a single comb line, while suppressing the unwanted tones by $>$ 35 dB. Secondly, the tunability is shown, by

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demultiplexing different tones of an OFC with FSRs varying from of 2.5 to 15 GHz. Then, we demonstrate that for all the demultiplexed lines within 10 dB from the spectral peak, a constant output power of 7.5 dBm and a suppression of other tones > 30 dB can be achieved. Finally, the stability of the demultiplexer is verified by filtering two comb tones, (separated by 1.25 GHz) beating them on the photodiode and measuring the frequency, power and linewidth of the resultant RF signal. To the best of our knowledge, this is the first demonstration of demultiplexing two lines of an OFC with an FSR smaller than the injection locking range of the demultiplexer.

2. Experimental results and discussion

The proposed architecture for the comb-based transmitter system is shown in Fig. 1(b). The OFC is injected into a semiconductor laser, acting as the demultiplexer. The wavelength of the demultiplexer is temperature tuned to match that of the desired comb tone. Consequently, the demultiplexer is injection locked by the tone (i.e. inherits its frequency and phase). The insets (i)-(iii) in Fig. 1(c) show line graphs of the optical spectra of the comb and the demultiplexer before and after injection locking. Since the output power of the demultiplexer is much higher than that of the input tone, the selected line is de facto amplified. The power difference between this line and the highest undesired tone, termed as the comb line suppression ratio (CLSR), is a vital performance metric of the demultiplexer.

As a proof of principle, we present a two-channel active demultiplexer, as depicted in Fig. 1(c). Firstly, we characterize the operation of a single demultiplexer. Secondly, we combine the output of the two demultiplexers, filtering two different comb tones, and perform a stability test. It is important to mention that the proposed demultiplexer technique can be used with any type of OFC. In this article, we chose an externally injected gain-switched laser (EI-GSL) [9,10] due to its FSR flexibility. The spectrum of the 6.25 GHz EI-GSL OFC, consisting of 8 comb lines (within 3 dB from the spectral peak) and portraying an optical carrier to noise ratio (OCNR) > 50 dB, as shown in Fig. 2(a) (OCNR and all spectra measured using a 20 MHz high resolution optical spectrum analyzer (OSA)).

2.1. Active demultiplexers

Two commercially available distributed feedback lasers (DFBs), with output powers of 7.5 dBm, are used as the demultiplexers. The optical spectrum of the free running demultiplexer 1 is illustrated in Fig. 2(c). The generated OFC is injected into the demultiplexer via a circulator. An inline variable optical attenuator (VOA) is used to adjust the injected comb line power (CLP). Here, the CLP is the power of the comb line that injection locks the demultiplexer. The CLP set to –32 dBm (as shown in Fig. 2(b)), results in a CLSR of 35 dB, as depicted in Fig. 2(d). The optical spectra of the demultiplexer with CLSR of 30 and 22.5 dB are as shown in Fig. 2(e) and (f), respectively.

2.1.1. CLSR dependency on CLP

To verify the performance of the demultiplexer, we first characterize the dependence of the CLSR on the injected CLP. To this effect, we vary the CLP from –32 to –10 dBm, with the aid of a VOA and record the obtained CLSR. Fig. 3(a) illustrates a plot (red) of the CLSR as a function of the CLP. From the figure it can be seen that the CLSR is inversely proportional to the CLP. This indicates that the CLSR is dictated by the difference between the power of the demultiplexer (free running case) and the power of the injected undesired comb tones. Another aspect of the proposed technique, related to the output power of the demultiplexer, is its ability to act as a low noise optical amplifier. The power of the comb line injected to the demultiplexer can be as low as –32 dBm while its power at the output of the demultiplexer is 7.5 dBm (fixed). Thus, the device provides up to 40 dB gain and can be viewed as an ultra-low noise amplifier (no ASE noise added) operating in a constant power mode. This is a direct consequence of the regenerative property of OIL [11].

2.1.2. CLSR dependency on detuning

The two tests mentioned above are carried out when the wavelength of the demultiplexer was perfectly aligned (within the 20 MHz resolution of the OSA) with the chosen comb line. However, it is well known that the wavelength of a semiconductor laser may drift over time. Therefore, it is important to characterize the tolerance of the demultiplexer to the wavelength detuning (Δf) i.e. the difference between the injected wavelength and the emission wavelength of the demultiplexer. The stable locking range can then be obtained by varying the detuning and ensuring that the output spectrum of the slave laser remains single moded. We measure the CLSR as a function of Δf for various CLPs and plot the results in Fig. 3(a). The detuning is varied from −2 to + 2 GHz, in steps of 250 MHz, where the negative values indicate that the wavelength of the demultiplexer is longer than that of the comb line. From the plot it is evident that the CLSR degrades as the detuning increases, with the highest CLSR value achieved for the perfect alignment (zero detuning). This can be attributed to the efficiency of the injection locking. It also shows that, the stable locking range of the demultiplexer is injection power dependent and increases from ± 750 MHz (CLP = –32 dBm) to ± 2 GHz (CLP = –22.5 dBm).

2.1.3. Phase noise analysis

As mentioned earlier, another attractive feature of the proposed demultiplexing technique is the transfer of the phase characteristics from the input OFC to the demultiplexed line. As a result, the device

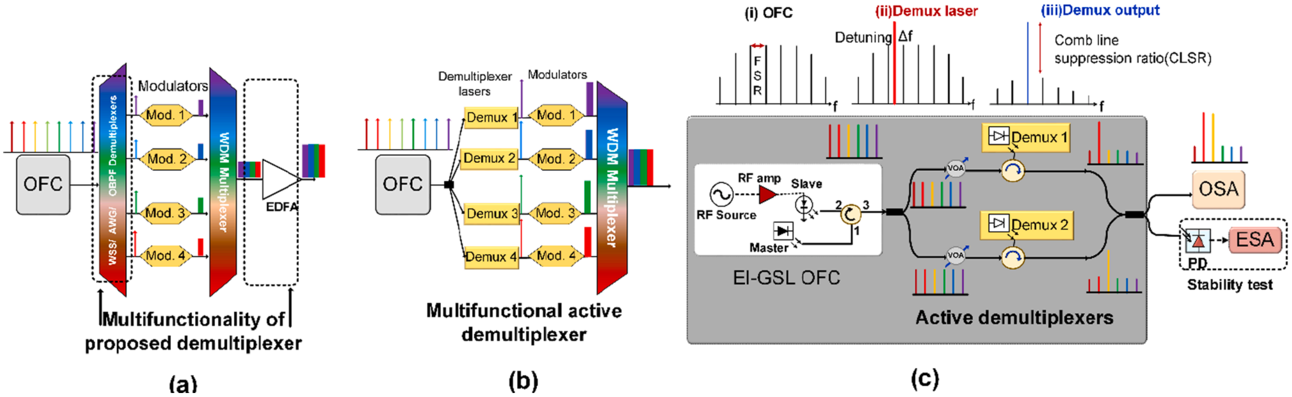

Fig. 1. Comb-based WDM transmitter using **(a)** a conventional and **(b)** the proposed multifunctional demultiplexer; **(c)** experimental setup of the proposed two-channel demultiplexer (insets (i)-(iii) showing the demultiplexing operation). Here Δf: detuning frequency; PD: photodetector; OSA: optical spectrum analyzer (fixed optical attenuator of 7 dB used); ESA: electrical spectrum analyzer.

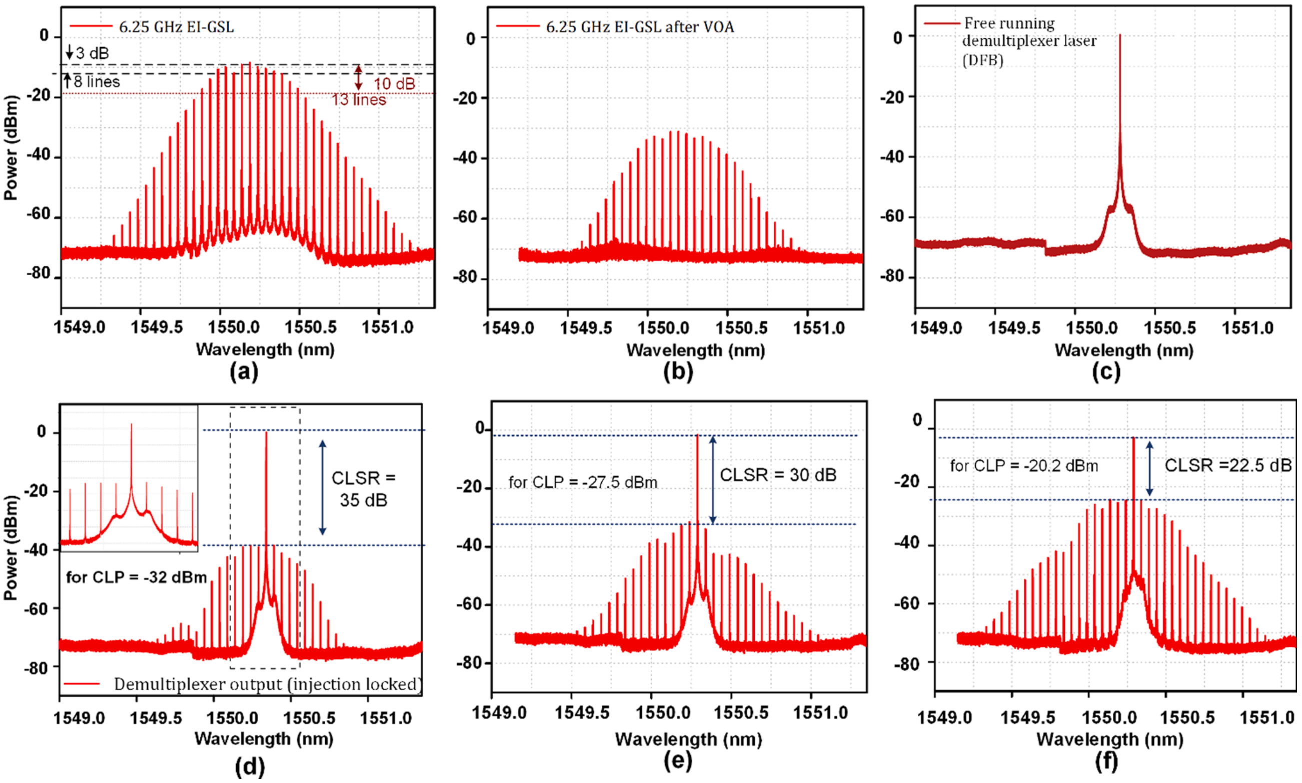

Fig. 2. Optical spectra (a) EI-GSL OFC with FSR = 6.25 GHz, (b) OFC after VOA (for CLP = –32 dBm), (c) free-running demultiplexer laser, (d) demultiplexer output with CLSR = 35 dB (inset shows the enlarged version of the dotted region), demultiplexer output for (e) CLP = -27.5 dBm (CLSR = 30 dB), (f) CLP = -20.2 dBm (CLSR = 22.5 dB). OSA resolution: 20 MHz, spectra saved with 7 dB attenuation.

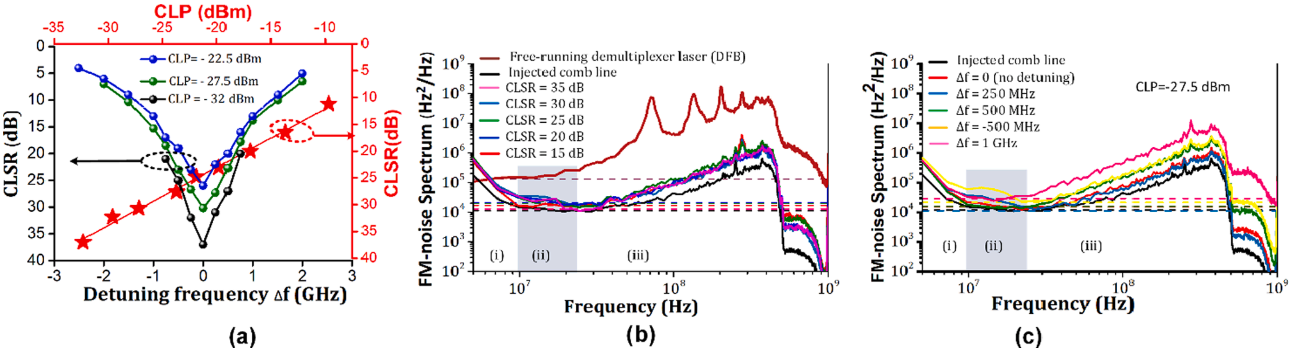

Fig. 3. Plot of (a) CLSR as a function of detuning and CLP; FM noise spectra: (b) for CLSR from 15 dB to 35 dB (for Δf = 0) and (c) for detuning frequency up to 1 GHz.

maintains the phase correlation between the comb lines, which is vital for applications such as millimeter wave and THz generation [12], atomic clocks [13] dual comb spectroscopy [14] etc. In order to validate the transfer of phase characteristics from the comb to the demultiplexer, we carry out frequency modulated (FM) noise spectrum measurements, using a modified-delayed self-heterodyne technique [15]. These tests are carried out for different values of CLP (thus CLSR) and detuning and plotted in Fig. 3(b) and (c) respectively. The FM noise spectrum $S_f(f)$ is the power spectral density of instantaneous frequency fluctuation (Hz^2/Hz). It may consist of (i) flicker noise (low frequency ($1/f$)), (ii) white noise (S_0, determining the actual laser linewidth) and (iii) random-walk (high frequency ($1/f^2$)) noise. The grey colored section in Fig. 3(b) and (c) is the approximation demarcation of the flat white noise part. The Lorentzian shaped laser linewidth (δf), can be calculated, by retrieving the flat part of the FM noise spectrum using the equation $\delta f = \pi \times S_0/2$ [15]. Due to the nature of heterodyne measurement, the S_0 is divided by a factor of 2. The colored dotted line in these plots is the flat S_0 values that are considered for the linewidth calculations in the respective cases. The drop in the values beyond 500 MHz corresponds to the bandwidth of a digital filter used in the offline processing of the data [15]. From the plots in Fig. 3(b), the linewidth of the free-running demultiplexer, the input OFC and the injection-locked demultiplexer (with zero detuning) are ~2.6 MHz, 19 kHz and 20 kHz, respectively. The three orders of magnitude linewidth reduction is a clear indication of the efficient phase transfer between the comb and the demultiplexer, due to stable OIL. Next, we repeat the measurements for a constant CLP of –27.5 dBm and different values of wavelength detuning. The results, presented in Fig. 3 (c), show that the white and the high frequency noise ($1/f^2$) of the demultiplexed line increase as the detuning increases. Thus, in order to maintain a low linewidth of the demultiplexed comb tone, the detuning value should be kept below ± 500 MHz.

2.2. Tunability and gain equalizer

Another attractive feature of the proposed demultiplexing technique is its tunabilty, allowing for the selection of an arbitrary line from OFCs with an arbitrary FSR. This unique aspect makes the proposed demultiplexer an ideal candidate for application in elastic optical networks, requiring dynamic reconfiguration of the transmitters. To demonstrate this tunability feature, the device is used to select three different lines from OFCs with FSRs of 2.5 GHz for CLP = –32 dBm, 6.25, 12.5 and 15 GHz for CLP = -27.5 dBm. The spectra of these combs are shown in Fig. 4 (a)-(d), with the selected lines marked by arrows. The corresponding output spectra of the demultiplexer, in Fig. 4(e)-(g), shows that a CLSR > 30 dB can be achieved for any line within 10 dB from the peak (line with sufficient power to achieve injection locking). This result clearly demonstrates that the proposed demultiplexer can be tuned in wavelength by 2 nm and would be able to demultiplex all lines within that range that possess adequate power for OIL. It can also be used to enhance the number of comb lines available for data modulation (ordinarily defined as tones with powers within 3 dB from the spectral peak). The number of usable lines, for the OFC used in this article, was increased by a factor of 1.7 (from 26 to 36, 8 to 13, 4 to 7, and 3 to 5 for an FSR of 2.5, 6.25, 12.5 and 15 GHz respectively). It is important to note that in each case, the efficient phase transfer (low linewidth of < 35 kHz) is achieved and an amplified output power of 7.5 dBm is maintained.

2.3. Stability

Finally, we carry out a stability analysis of the demultiplexer operation. We filter out two adjacent tones from the OFC (Fig. 5 (a)) with an FSR of 1.25 GHz as shown in Fig. 5(b), at a CLP of –32 dBm. Such a configuration, power at which the locking range is 1.5 GHz (from Fig. 3 (a) and both selected tones lie within that locking range) makes the demultiplexer prone to stability issues. The demultiplexed tones are then combined and detected on a high-speed photodiode. The optical spectrum of the combined outputs of both demultiplexers is shown in Fig. 5 (b). The resultant RF beat tone is presented in Fig. 5(c). The power, linewidth and frequency of the generated RF beat tone is monitored over 30 min and recorded at intervals of 5 s. During the test, the frequency span of the ESA is set to 1 kHz and the resolution bandwidth to 30 Hz. The plot of the frequency of the beat tone as a function of time is depicted in Fig. 5(d). The stability of the generated tone is lower than 120 Hz, which is comparable with the stability of the RF synthesizer used for the OFC generation. Fig. 5(e) shows the corresponding plot of the beat tone power (red) and linewidth (blue). From the plot it can be seen that the power fluctuation is <2 dB, which is caused by a variation in the polarisation and could be further reduced by using polarisation maintaining fiber. The beat linewidth remains constant ~34 Hz (limited by resolution of ESA). This narrow linewidth is a reflection of the high degree of phase correlation between the demultiplexed tones, which in turn proves that stable locking is maintained throughout the duration of the test. Further, the phase correlation measurement is extended to the demultiplexed tones that are frequency separated between 2.5 GHz and 37.5 GHz. The resultant 3 dB beat tone linewidth measured as 34 Hz, as shown in Fig. 5(f). Overall, the results presented in Fig. 5(d)-(f) demonstrate the exceptional stability of operation of the demultiplexer, even under critical conditions.

3. Conclusions

In conclusion, a multifunctional active demultiplexer is proposed and a comprehensive characterization is presented. The proposed technique achieves a constant output power of the filtered comb line, as long as the CLP is sufficient to injection lock the demultiplexer. Thus, the demultiplexer can also be viewed as an amplifier working in a constant power mode. The described technique allows for the transfer of the original phase characteristics of the comb on to the selected line. This is verified by the FM-noise analysis showing three orders of magnitude reduction in the demultiplexer linewidth (MHz to kHz). The tunability and flexibility of the scheme are also highlighted, by demultiplexing lines for combs with FSRs of 2.5, 6.25, 12.5 and 15 GHz. In addition, the gain equalizer functionality is illustrated, by showing that all lines, within 10 dB from the peak, can be successfully demultiplexed (CLSR > 30 dB and output power of 7.5 dBm). This increases the number of comb lines usable for data modulation to ~1.7 times. Finally, the stability test proves that even at low CLPs and channel spacing, the demultiplexer portrays a highly stable beat tone frequency, power and linewidth. The proposed multifunctional device can be photonically integrated with the comb, removing the need for VOAs and optical circulators, thus reducing the footprint, cost and complexity of the transmitter. With all

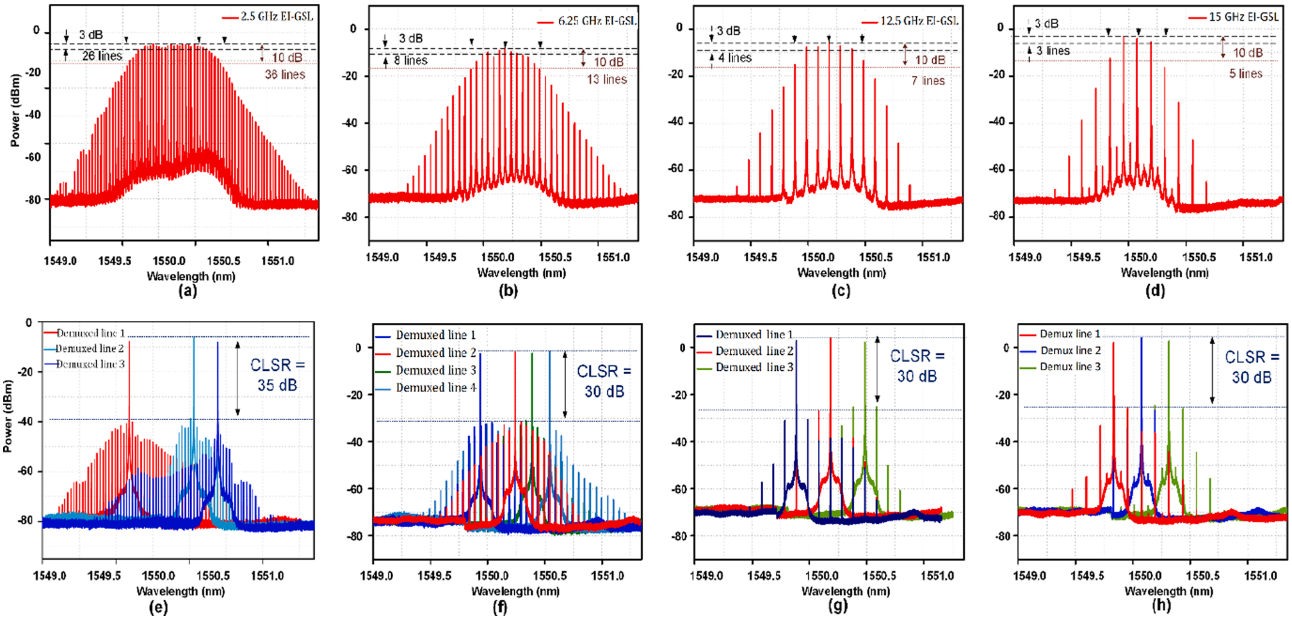

Fig. 4. Optical spectra of (a) - (d) the OFC and (e) - (f) demultiplexed outputs for FSR of 2.5, 6.25, 12.5 and 15 GHz. OSA resolution: 20 MHz, spectra saved with 7 dB attenuation.

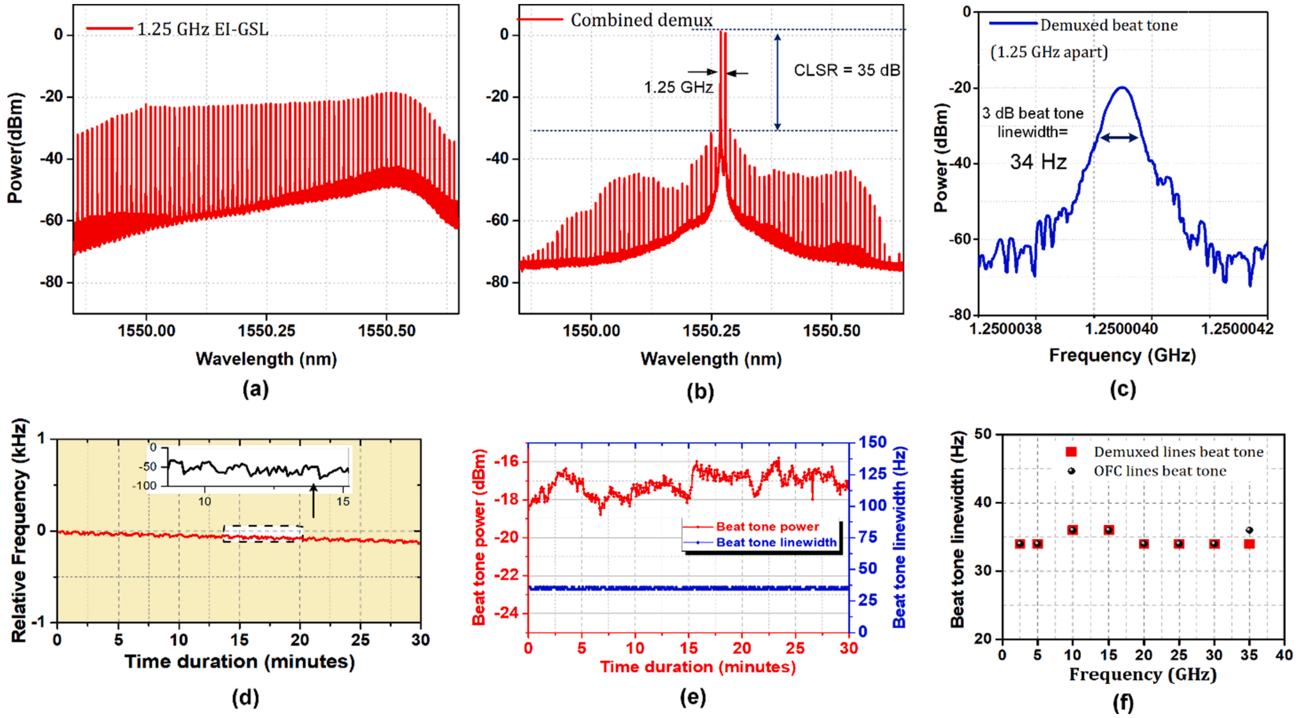

Fig. 5. Optical specta of (a) the OFC with FSR = 1.25 GHz, (b) two demultiplexed lines (1.25 GHz apart) with CLSR of 35 dB; (c) electrical spectrum of beat tone; stability test results: (d) relative frequency vs. time, (e) beat tone power (red) and linewidth(blue) vs. time and, (f) phase correlation measurement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

these excellent features, the proposed active demultiplexer is a promising candidate for employment in flexible superchannel-based optical networks.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.optlastec.2020.106637.

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