Generation of 103 ultra-flat broadband optical frequency comb lines using cascaded amplitude modulator and single drive Mach-Zehnder modulators

K. JEYAPIRIYA*, M. BASKARAN*
Sri Sairam Engineering College, Chennai, India

This paper presents the method of generation of ultra-flat broadband optical frequency comb using an Amplitude modulator (AM) and two Single Drive Mach-Zehnder modulators (SD-MZM) in cascade. Modulating signal of 30 GHz frequency is fed to the modulators with the carrier signal of 193.1THz. The modulated signal from the AM is directly fed to one SD-MZM. The AM output is also frequency shifted by 5GHz and fed to another SD-MZM. Both the SD-MZMs are designed with an extinction ratio of 30 dB and a symmetry factor of 0.955. This results in the production of 103 spectral lines with power ripple between each spectral tone to be less than 1 dB. While comparing with previous techniques, this simple cascaded configuration gives 103 ultra-flat spectral tones with a frequency repetition rate of 12 GHz. Each carrier generated from this method can act as a source for Wavelength Division Multiplexing – Passive Optical Networks (WDM-PON). This resolves the need for the broadband capability for the next generation network.

(Received June 27, 2024; accepted October 7, 2024)

Keywords: Single drive Mach-Zehnder modulator, Extinction ratio, Symmetry factor, WDM-PON

1. Introduction

The optical field is actively searching for new methods to boost the deployed optical networks' overall capacity in order to handle the extraordinary surge in Internet traffic brought on by the emergence of bandwidth-hungry applications. Innovative solutions must be scalable, inexpensive, and simple to deploy. The next generation passive optical network is aimed to boost bit-rate, which is a significant step in the direction of high performance. Wavelength Division Multiplexing (WDM) is one of the methods used to increase data rate. Increasing the number of WDM channels while maintaining the same bit-rate per channel can increase the overall capacity and to attain high bit rate. Consequently, the WDM-PON offers a suitable technology that will be applied as the network of the future. For the WDM channels, a spectrum multicarrier optical source is formed using Optical Frequency Comb(OFC). Optical source produces separate longitude modes and equally spaced comb lines which are called OFC. In general, a flat frequency comb is preferred. It is preferable to have similar power in each wavelength if the comb is utilised, for instance, as a multi-wavelength source. Starting with a flat comb makes apodization considerably easier and results in less extra loss for applications like RF photonic filtering that require a precise spectral shape [1]. OFCs found quick applications in solid-state, atomic, photonic, and molecular systems. Attosecond pulse generation [2], control of attosecond pulse processes [3], molecular technology of fingerprinting [4], gas sensing in the oil and gas industry [5], tests of fundamental atomic clock physics, calibration of atomic spectrographs, precise time and frequency transmission across fibre and free space, measurements of arbitrary waveforms for optical communication, and accurate ranging [6] were some of the other applications.

Passive mode-locked erbium-doped fibre lasers [7] - [8] are used in several OFC generation techniques. To preserve stability, Mode Locked Laser necessitates intricate and exacting phase locking configurations. OFC generators with fibre nonlinearities [9] have also been proposed, but large optical amplifiers and complex constructions are required for this technology.

Because of its simplicity and stability, OFC generation methods based on EO modulator have received a lot of attention [10]- [11]. With this approach, OFC can be produced with a single modulator [12]- [13] and the system is straightforward but produces a lesser amount of comb lines. Increasing the number of modulators can increase the comb lines. For instance, an OFC with 25 comb lines can be created by connecting polarization modulators with a power fluctuation that is within 1 dB [16]. There have been various suggested solutions to the aforementioned issues. Flat OFCs with more of comb lines can be produced by a two-stage structure implementing polarisation modulators and a Mach-Zehnder interferometer [14] -[15].

2. System design for OFC generation

The spectrum of OFC is made up of equidistant comb lines and distinct longitude modes. In theory, OFC manifests as an ultrashort optical pulse with a femtosecond time duration in the time domain and as equally spaced frequency sequence in the frequency domain. The OFC's optical pulse sequence and spectrum both meet Fourier transform requirements.

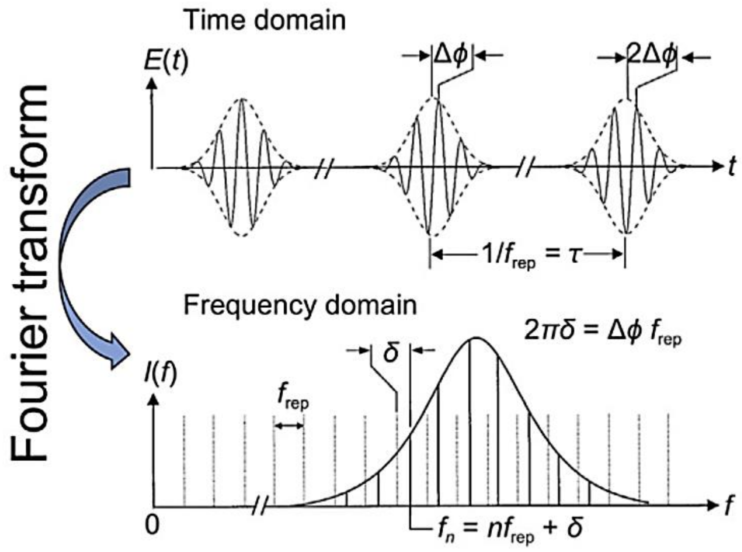

Fig. 1. Time domain and Frequency domain of OFC (color online)

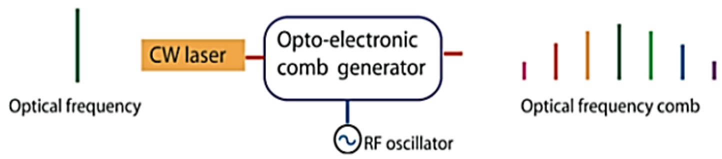

Fig. 2. OFC generation method (color online)

Opto- electronic comb generators are EO modulators like a push-pull Mach-Zehnder modulator (MZM), an in-phase and quadrature (IQ) modulator, a polarisation modulator, a phase modulator (PM), or a micro-ring modulator [17]- [18]. They can be used to create an EO frequency comb. Nevertheless, the OFCs produced with a single EO modulator typically have poor power flatness. The effective solution to this issue is to cascade one or more PMs [19].

MZM is an EO modulator in which the modulator arms' refractive index varies in response to changes in the applied electric field. It consists of two waveguides that act as the interferometer's arms. The input waveguide, to which the laser is attached, is split into two channels, each of which has electrodes surrounding it. Because of the shift in refractive index caused by the modulated signal and DC bias voltage, each arm's refractive index is altered, resulting in modulation of phase. By connecting the interferometer's arms, the phase modulation is ultimately converted to intensity modulation. By adjusting the sidebands' power deviation, the intensity modulator's nonlinear effect flattens the spectrum at the MZM output. In this case, two MZMs with a single drive are used and each arm receives the same modulation voltage [20].

The frequency domain expression of OFC [12] can be expressed as

$$f_{comb} = f_{offset} + nf_{rept} \tag{1}$$

where f_{offset} denotes the carrier offset frequency, f_{rept} denotes the spacing between the successive pulse, and n being the order of OFC. The nth order comb is obtained after frequency multiplication and can be expressed as

$$2f_n = 2\ f_{CEO} + 2nf_{rept} \tag{2}$$

The 2nth order comb line frequency is

$$2f_{2n} = f_{CEO} + 2nf_{rept} \tag{3}$$

The optical output power of the source, a continuous wave (CW) laser, is time invariant. An external modulator is a voltage-driven device, meaning that the input voltage determines the optical light intensity. Fig. 3 displays the schematic diagram of the suggested OFC generator, which includes one AM, two SD-MZMs, and a CW laser. A 30 GHz radio frequency signal is fed into the modulators.An external RF oscillator powers one or more modulators in an optical system that receives a continuous-wave (CW) laser. The oscillator frequency fixes the frequency spacing, while the CW laser defines the core wavelength, resulting in the formation of a comb at the output.

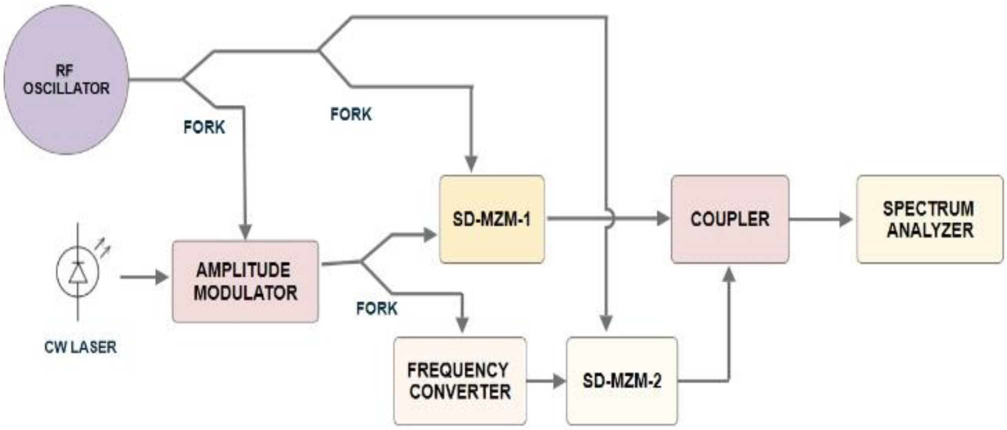

Fig. 3. Block diagram of the proposed system (color online)

The phase of the signal in the waveguide is varied in accordance with the input voltage and is given by the relation

$$\Delta\phi = V(t)\left(\frac{\pi}{v_\pi}\right) \tag{4}$$

The optical signal to the input port of SD-MZM-1 [7] - [8] is given as

$$E_{\text{in}}(t) = E_0 e^{j\omega_0 t} \tag{5}$$

where E_0 is the intensity and ω_0 is the angular frequency of the signal. The output from SD-MZM-1 [21] can be expressed as

$$E_{\text{out}}(t) = \frac{1}{2}E_{\text{in}}(t)\left\{e^{j\left[\pi\frac{V_{1(t)}}{V_\pi}\right]} + e^{j\left[\pi\frac{V_{2(t)}}{V_\pi}\right]}\right\} \tag{6}$$

where v_π is the half-wave voltage of the MZM. $V_1(t)$ and $V_2(t)$ are the driving signals applied to both the arms of SD-MZMs , respectively, and

$$\begin{aligned} V_1(t) &= V_{\text{dc1}} + V_{\text{rf1}}\cos(\omega_{\text{rf1}}t + \varphi_1) \\ V_2(t) &= V_{\text{dc2}} + V_{\text{rf2}}\cos(\omega_{\text{rf2}}t + \varphi_2) \end{aligned} \tag{7}$$

where φ_1 and φ_2 are the respective phase of the two driving signals, ω_{rf1} and ω_{rf2} are their angular frequencies.

Finally, when $V_{\text{rf1}} = V_{\text{rf2}}, \omega_{\text{rf1}} = \omega_{rf2}$, the equation becomes,

$$\begin{aligned} E_{\text{MZM1}}(t) &= \alpha E_0 \exp(-j\omega_0 t)\cos\left(\frac{\varphi_{DC}}{2} + x.\cos(\omega_{RF}t)\right) \\ &= \alpha E_0 \exp(-j\omega_0 t)[K] \end{aligned} \tag{8}$$

where

$$x = \frac{m_{MZM}}{2} \ \&$$

$$K = \sum_{n=-\infty}^{\infty} \cos\left(\frac{\varphi_{DC}}{2} + \frac{n}{2}\pi\right) J_n(x)\exp(jn\omega_{RF}t)$$

The intensity modulated signal is also shifted by Δf in the frequency domain and is given to the input port of SD-MZM-2. The output of SD-MZM-2 [7] - [8] becomes,

$$A = \sum_{n=-\infty}^{\infty} \cos\left(\frac{\varphi_{DC}}{2} + \frac{n}{2}\pi\right) J_n(x)\exp(jn(\omega_{RF} + \Delta f)t) \tag{9}$$

$$E_{\text{MZM2}}(t) = \alpha E_0 \exp(-j\omega_0 t)[A] \tag{10}$$

where E_0 is the intensity and ω_0 is the center angular frequency of the CW light from Laser . α is the power loss due to fiber-to-chip coupling.

$$m_{MZM} = \pi V_{RF}/V_{\pi\_MZM} \tag{11}$$

m_{MZM} is termed as the modulation index and

$$\varphi_{DC} = \pi V_{\text{bias}}/V_{\pi\_DC} \tag{12}$$

φ_{DC} is DC bias of the MZM. V_{π_MZM} is the RF half-wave voltage of MZM and V_{π_DC} is the DC half-wave voltage of the MZM. V_{bias} is the DC voltage and V_{RF} is the RF signal applied to the MZM.

Final comb from the coupler is given by

$$B = \sum_{n=-\infty}^{\infty} \cos\left(\frac{\varphi_{DC}}{2} + \frac{n}{2}\pi\right) J_n(x)\exp(jn\omega_{RF}(1 + \Delta f)t) \tag{13}$$

$$E_{COMB}(t) = \alpha E_0 \exp(-j\omega_0 t)[B] \tag{14}$$

The frequency is altered in accordance with the frequency of the RF signal as it passes through the modulator. SD-MZM-1 uses a CW laser with a 14.2 dBm power output at 1550.02 nm as its seed carrier. The power level in the side bands can be adjusted by the amplitude of the RF signal and the DC reverse bias. Then, by using another SD-MZM-2, the number of sidebands gets improved.

3. Results and discussions

The Opti system software is used here to analyze the proposed system. The final output is read using optical spectrum analyzer (OSA) of 0.01 nm resolution. Each and every setting on the laser source and modulators is adjusted so that the generated spectrum has carriers with equal power distribution. The system parameters for the design are set as mentioned in the Table 1. By setting the laser's power at 15 dBm and line width at 10 MHz, the output of the device depicted in Fig. 8 can be achieved. The frequency of the RF signal generator is set to 30 GHz.

In order to amplify the harmonics, the AM's output is immediately fed into a SD-MZM-1, which generates a 51-spectral line frequency comb with a driver signal at 30 GHz. Additionally, the ideal frequency converter uses the AM output as its input, with a fixed frequency shift of 5 GHz. In order to improve the harmonics obtained from AM, where the frequency shifted 51 spectral lines are obtained as output, the frequency shifted AM output is then fed as an input to SD-MZM-2. The more improved 103 spectral line frequency comb output is produced by cascading the frequency-shifted output from SD-MZM-2 and the output from SD-MZM-1 using an optical coupler.

The RF signal is sent to MZMs and AM, where the symmetry factor is set at 0.955, the extinction ratio of MZM is set between 35 and 40 dB, and the modulation index "m" is fixed at 1. The amount of harmonics produced by MZM is dependent on the extinction ratio.The ratio of the peak transmission power to the minimum transmission power is known as the extinction ratio (ER), and it is expressed in decibels (dB) [8].

Table 1. List of simulation parameters

Parameters	*Values*
CW laser frequency	193.1THz
Bias voltage 1	-2.8 volts
Bias Voltage 2	-1.1 volts
RF frequency	30 GHz
Extinction ratio	30dB
Symmetry Factor	0.955

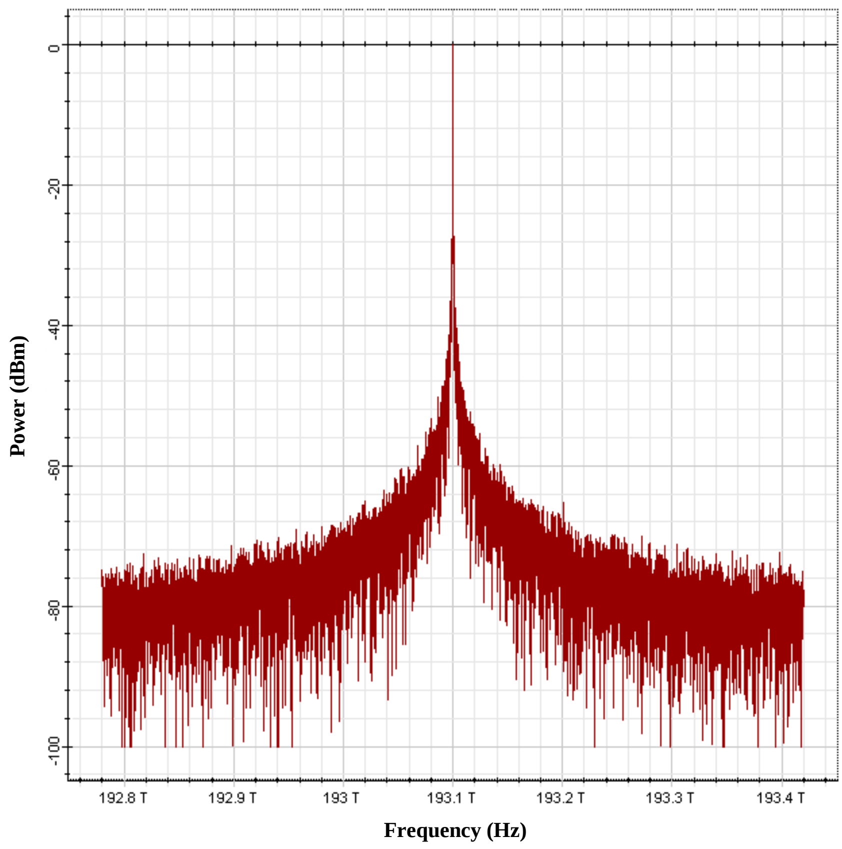

Fig. 4. Laser source output (color online)

The output of the Laser source shown in Fig. 4 is sent to AM. The AM output in Fig. 5 shows the spectrum containing sidebands, out of which only few carry information because the sideband level detoriates as the order increases. So to further increase the OFCs the AM output is send to SD-MZM-1 and driven by 30 GHz RF signal. Power at center frequency is noted to be 8 dBm and at side bands power goes on decreasing which results in unwanted harmonics. To perform reliable data transmission, these harmonics are powered up by using SD-MZMs. Both SD-MZMs are driven at peak operating condition to get all the spectral components.

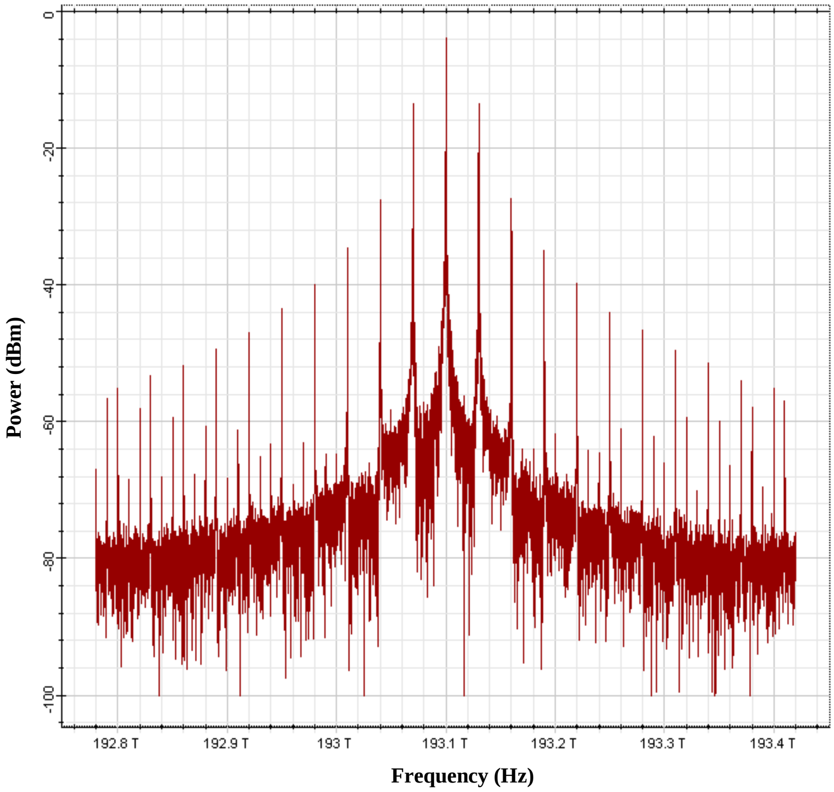

Fig. 5. Output of the amplitude modulator (color online)

From Fig. 6 and Fig. 7, power excursions between each spectral tone are found to be precisely at 0.909 dBm. Every carrier produced by this method supports as a supply for WDM-PON [21] to increase the data rate of the network of the future.

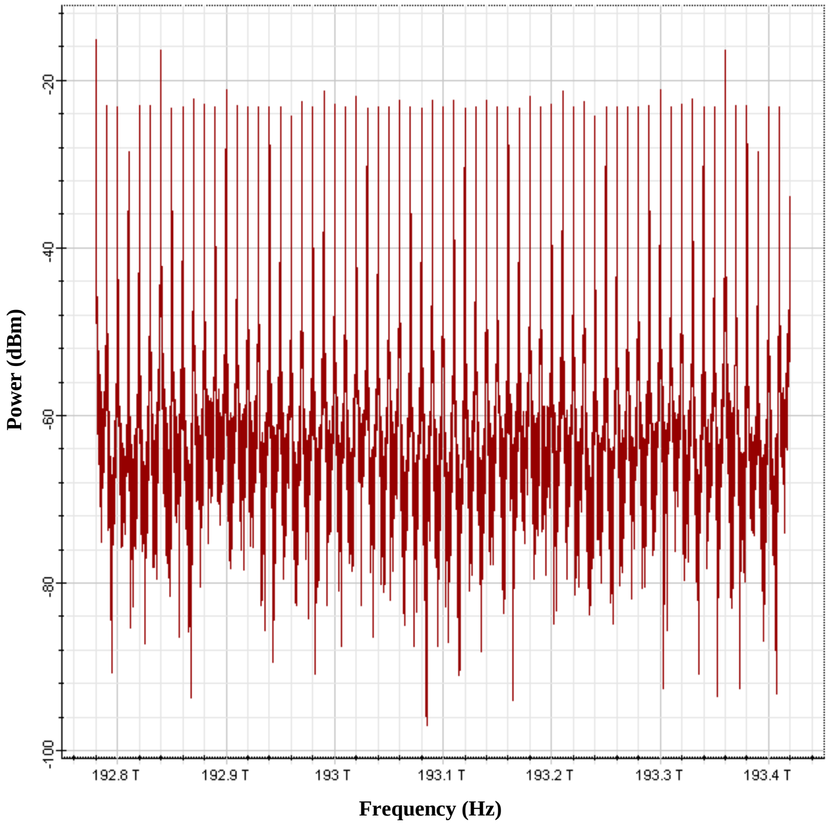

Fig. 6. SD-MZM-1 output with 51 comb lines (color online)

While comparing with previous techniques, it is noted that the proposed system gives large number of spectral tones in cascaded configuration of modulators with power excursions to be 0.909dBm.

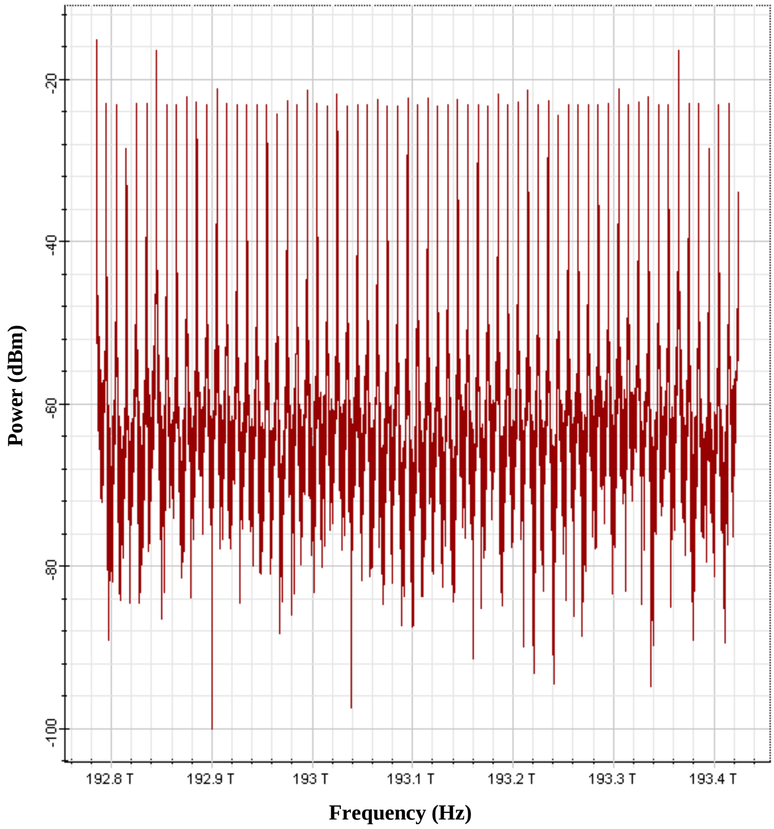

Fig. 7. SD-MZM-2 output with 51 comb lines (color online)

By properly biasing the modulators to the threshold point and with the parameters set as in table, a large number of frequency components are produced. The outputs of both SD-MZMs shown in Fig. 6 and Fig. 7 are then coupled which eventually result in an OFC of 103 spectral lines shown in Fig. 8.

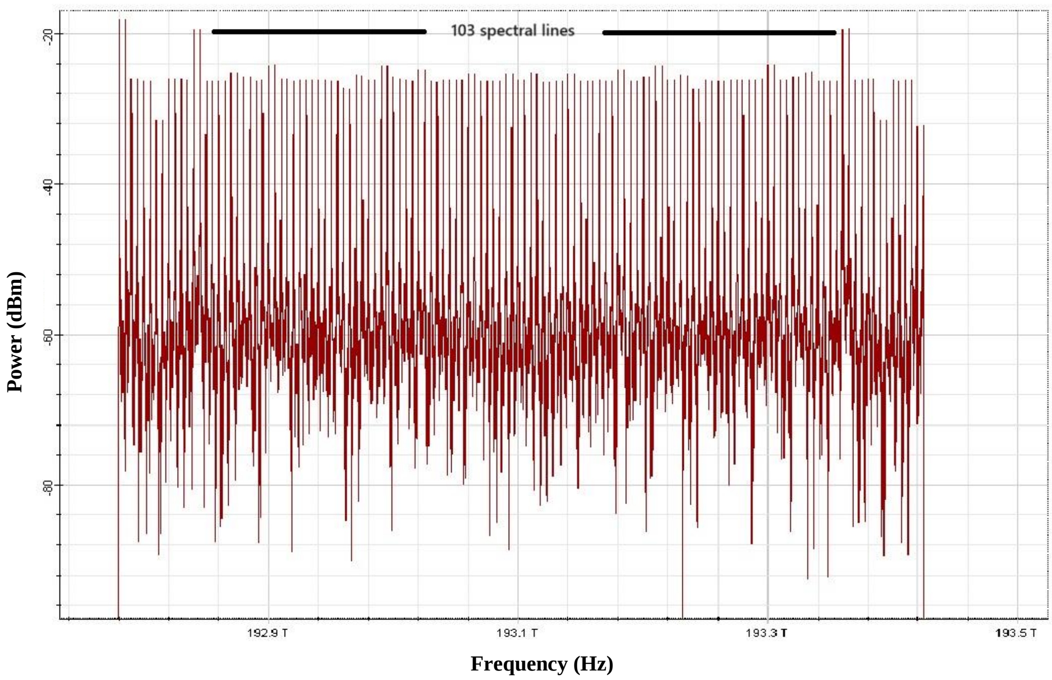

Fig. 8. 103 Frequency comb lines output from the proposed system (color online)

4. WDM-PON system using OFC generation

In Fig. 9, OFC is the Optical frequency comb, OSA is the Optical Spectral Analyzer, FC is fiber collimater ranging from 1 to N for N channels and WDM is the Wavelength Division Multiplexer.

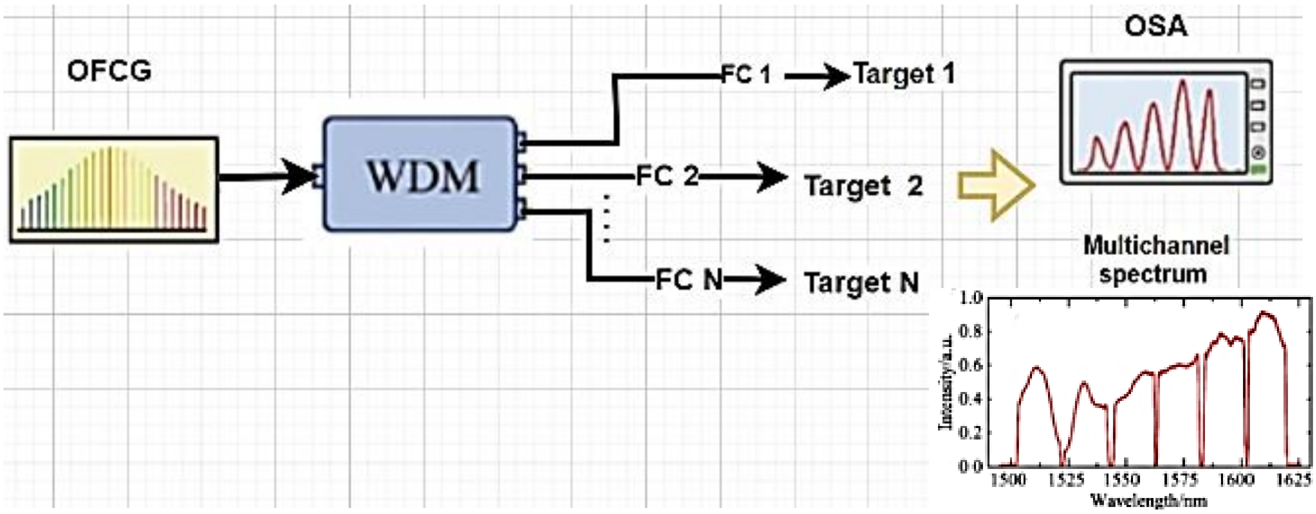

Fig. 9. Schematic of WDM-PON system (color online)

Across a wide range, optical frequency combs provide a succession of precisely spaced and matched light frequencies. The WDM system may create wavelength channels that are clearly defined and closely spaced by properly tuning these frequencies to match particular wavelengths. Within the available optical spectrum, WDM systems can support more wavelength channels by utilising the precise optical frequencies produced by the frequency comb. Multiple data streams can now be transmitted simultaneously over a single optical fibre because to this improved capacity.

Different and well-separated wavelengths are provided by the equally spaced OFC lines. By keeping channels apart, interference between them is reduced, making it possible for signals sent at various wavelengths to be effectively demultiplexed at the receiving end. Optical frequency combs allow for effective packing of wavelength channels, maximising the use of the available optical spectrum. By ensuring that the system makes the best use of the available bandwidth, this spectral efficiency raises the system's total data transmission capacity. Adding OFC to WDM systems makes them more versatile. In order to effectively utilize the resources at hand and to satisfy the upgrading network requirements, this technology enables the dynamic allocation and reallocation of wavelengths in response to demand.

5. Conclusion

A cost effective system has been proposed for the generation of OFCS that can be deployed in WDM-PON. Instead of using large number of laser sources, the proposed system generates comb using a single AM and cascaded sd-MZM architecture. This technique entertains many users, where no attenuators, electrical amplifier, phase shifter or filters are used in OFCS generator. With proper biased modulators (AM and MZM), an 103 OFC with a frequency repetition rate of 12GHz and minimum power fluctuations less than 1 dBm between spectral lines is achieved. A thorough theoretical investigation is done on the outputs of this proposal and is suggested as better method to use at WDM-PON . Greater than 103 spectral lines can be achieved by cascading another single drive MZM to the proposed design. Thus the proposed model promises a High-capacity, broadband data transmission, Cost effective and least power fluctuations between carriers.

References

[1] D. E. L. Ehsan Hamidi, A. M. Weiner, IEEE Transactions on Microwave Theory and Techniques **58**(11), 3269 (2010).
[2] U. Keller, Nature **424**(6950), 831 (2003).
[3] A. Baltuska, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V. Yakovlev, A. Scrinzi, T. Haensch, F. Krausz, Nature **421**, 611 (2003).
[4] S. Diddams, L. Hollberg, V. Mbele, Nature **445**, 627 (2007).
[5] C. Alden, S. Ghosh, S. Coburn, C. Sweeney, A. Karion, R. Wright, I. Coddington, K. Prasad, G. Rieker, Atmospheric Measurement Techniques Discussions **10**, 1 (2017).
[6] K. Minoshima, H. Matsumoto, Applied Optics **39**, 5512 (2000).
[7] Stefan Preussler, Norman Wenzel, Thomas Schneider, Optics Letters **39**(6),

1637 (2014).
[8] L. L. T. Z. Wiberg, Optics Express **20**(26), B419 (2012).
[9] J.Tang, J., Optics Express **19**(5), 14682 (2011).
[10] F. Zhang, J. Wu, Y. Li, J. Lin, Optics Communications **290**, 37 (2013).
[11] L. Shang, A. Wen, G. Lin, Y. Gao, Optics Communications **331**, 262 (2014).
[12] A. Metcalf, V. Torres Company, D. Leaird, A. Weiner, IEEE Journal of Selected Topics in Quantum Electronics **19**, 231 (2013).
[13] Q. Wang, L. Huo, Y. Xing, B. Zhou, Optics Letters **39**(10), 3050 (2014).
[14] Y. Li, S. Wu, Y. Fei, Optik - International Journal for Light and Electron Optics **125**, 962 (2014).
[15] J. K. Hmood, S. D. Emami, K. A. Noordin, H. Ahmad, S. W. Harun, H. M. Shalaby, Optics Communications **344**, 139 (2015).
[16] C. He, S. Pan, R. Guo, Y. Zhao, M. Pan, Optics Letters **37**, 3834 (2012).
[17] K. Qu, S. Zhao, X. Li, Z. Zhu, D. Liang, D. Liang, IEEE Photonics Technology Letters **29**(2), 255 (2017).
[18] T. Sakamoto, T. Kawanishi, M. Tsuchiya, Optics Letters **33**(8), 890 (2008).
[19] Y. Dou, H. Zhang, M. Yao, IEEE Photonics Technology Letters **24**, 727 (2012).
[20] I. Demirtzioglou, C. Lacava, K. R. H. Bottrill, D. J. Thomson, G. T. Reed, D. J. Richardson, P. Petropoulos, Optics Express **26**(2), 790 (2018).
[21] M. Baskaran, M. S. M. Kishanlal, Journal of Nonlinear Optical Physics and Materials **33**(5), 2350054 (2024).

*Corresponding authors: priyainchrist@gmail.com; baski.maha@gmail.com