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Synergistic integration of dual-drive MZM and frequency modulators for ultra-flat optical frequency comb generation

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This manuscript presents optical frequency comb generation by employing two frequency modulators with dual drive Mach-Zehnder modulator. The modulator FM_1 is driven with radio frequency (RF) at 16 GHz, FM_2 at 8 GHz and DD-MZM at 32 GHz respectively. These RF signals are directly driven by modulator without need a phase shifter. The generated optical comb produces 81 frequency comb lines with 0.2 dB to 1.5 dB maximum power deviation and having frequency spacing of 4 GHz with bandwidth 852 GHz. A theoretical study is carried out to examine the smooth spectrum produced by a sequences of frequency modulators and Mach-Zehnder with simulation results validate these findings provide substantial support for the observed results. The generated setup is power efficient as well as reliable. This setup design is applicable for optical communication, metrology and radio frequency photonics.

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Keywords: Frequency modulator (FM), Dual drive Mach-Zehnder modulator (DD-MZM), Optical frequency comb (OFC), Maximum power deviation

1. Introduction

An Optical Frequency Comb (OFC) refers to a structured optical frequency spectrum that comprised various frequency components, which have even and odd number of sidebands with stable phase relationships [1], garnering significant interest with its applications in wavelength-division multiplexing (WDM) systems [2], optical arbitrary waveform generation [3] and photonic microwave signal processing [4]. There is ongoing research to develop OFCs with characteristics such as flatness, a large number of frequency comb lines, significant side mode suppression ratio (SMSR) and tunable bandwidth of generated comb. There are Various methods that utilises for generation of OFC which includes the mode lock approach [5], single modulator method [6], modulator including dispersion medium technique [7], cyclic frequency shift method [8] and cascade modulator method [9-12]. To simplify system complexity and enable tunable OFC spacing, a cascaded electro-optic modulator scheme has been proposed.

The development of an OFC generator by employing two cascaded intensity modulators capable of producing nine lines of optical comb having 2 dB flatness [9]. By cascading an intensity modulator (IM) with a phase modulator (PM), OFCs with 15 and 17 comb lines, featuring flatness of 1 dB and 3 dB respectively, have been generated [10]. Additionally, cascading IM with two PM can yield 29 frequency lines with 1.5 dB maximum power variation [11]. Furthermore, employing cascaded polarization modulators (PolMs) [13-15] have been employed in various setups for OFC generation in which two cascaded (PolMs) has resulted 25 OFC line with 1 dB flatness, although it exhibit less optical frequency lines and bandwidth in this configuration [12].

OFCs find utility across various domains, including optical waveform generation, photonic signal processing, metrology and DWDM transmission systems [16-19]. Numerous methods exist for OFC generation that includes a mode-locked laser can produce an OFC [20], it utilizes feedback loop for stability and facing challenges in tuning comb line spacing. Alternatively, fibre nonlinearities such as stimulated Brillouin scattering (SBS) and four-wave mixing (FWM) can generate OFC, but necessitate high-power optical amplifiers and intricate setups [21,22].

Another effective approach which is based on electro-optic modulator (EOM) [23] offers stability and adjustable spectral spacing. The optical comb lines generated by this method can be enhanced by employing a multi-stage OFC generator [24]. In Reference [25], a dual-parallel Mach-Zehnder modulator (DPMZM) [26] utilized for generating seven optical frequency comb lines requiring meticulous control of the DPMZM's three bias voltages to ensure optimal power uniformity. Alternatively, five comb lines are generated by employing a polarization modulator (PolM) and a Mach-Zehnder modulator (MZM) [12,27]. Furthermore, utilizing a PolM along with adjusting the power gap between sidebands via an optical amplifier can generate a seven-line OFC with satisfactory flatness [28]. This setup increases network complexity and power consumption due to optical amplifier usage. Another method to generate numerous comb lines with power uniformity involves RF sinusoidal signal which is phase modulated by applying input CW light into short optical pulses proves effective, achievable through additional intensity modulators [3,29]. Another method involves intensity and phase modulator that is driven by RF signal achieved 38 comb lines with 1 dB power with improved flatness in generated frequency comb [30].

This manuscript presents a method for generating an ultra-flat Optical Frequency Comb (OFC) that comprises frequency modulators with DD-MZM. This manuscript comprises different sections in which Section I includes introduction in which various approaches to design OFC has been explained. Section II comprises proposed setup to design optical frequency comb in which FM_1, FM_2 and DD-MZM at 16 GHz, 8 GHz and 32 GHz respectively. Initially generated number of optical lines are less in number with large value of maximum power deviation. To mitigate the maximum power deviation in generated comb and to increase the optical comb lines. FM_2 is employed in setup with DD-MZM which increases the number of subcarriers in generated optical comb. This section also includes the optimized parameter for proposed setup optical network. Whereas Section III include results and discussion in which performance analysis of generated OFC has been proposed. Conclusion Section includes the overall result of generated OFC with application of future optical network.

2. Proposed setup to analyse optical frequency comb

The setup design for ultra-flat OFC generation is illustrated in Fig. 1 that comprises CW laser having frequency 193.1 THz, power 10 dBm and linewidth 10 MHz. CW laser initiates the frequency comb with central frequency of OFC. The output of CW laser fed to the cascaded FM modulator that generates subcarriers. FM_1 generated subcarriers which are less in number whereas even and odd number of sidebands are produced when output of FM_1 get fed into FM_2. The modulator FM_2 generated large number of sidebands. The comb spacing between the generated subcarriers depend on the RF signal applied across the modulators. However, the power deviation is large at output of FM modulators which exhibit poor flatness of generated comb so output of cascaded modulators gets fed to DD-MZM.

The DD-MZM in generated optical network operates by utilizing electro-optic principle to induce changes in refractive index within its modulator arms. This modulation is achieved through the application of varying electric fields, controlled by electrodes surrounding the waveguides. These changes in refractive index result in phase modulation, as the laser input is split into two paths within the waveguides. By adjusting the biasing voltage and modulation voltage of DD-MZM the refractive index gets changes which leads to phase shifts in each arm of modulator. When the arms are recombined, these phase shifts translate into intensity modulation. Additionally, the non-linear effects of the intensity modulation serve to balance the spectrum output of DD-MZM by regulating the maximum power deviation of sidebands. The optimized value of all the component utilized in setup design is summarized in Table 1.

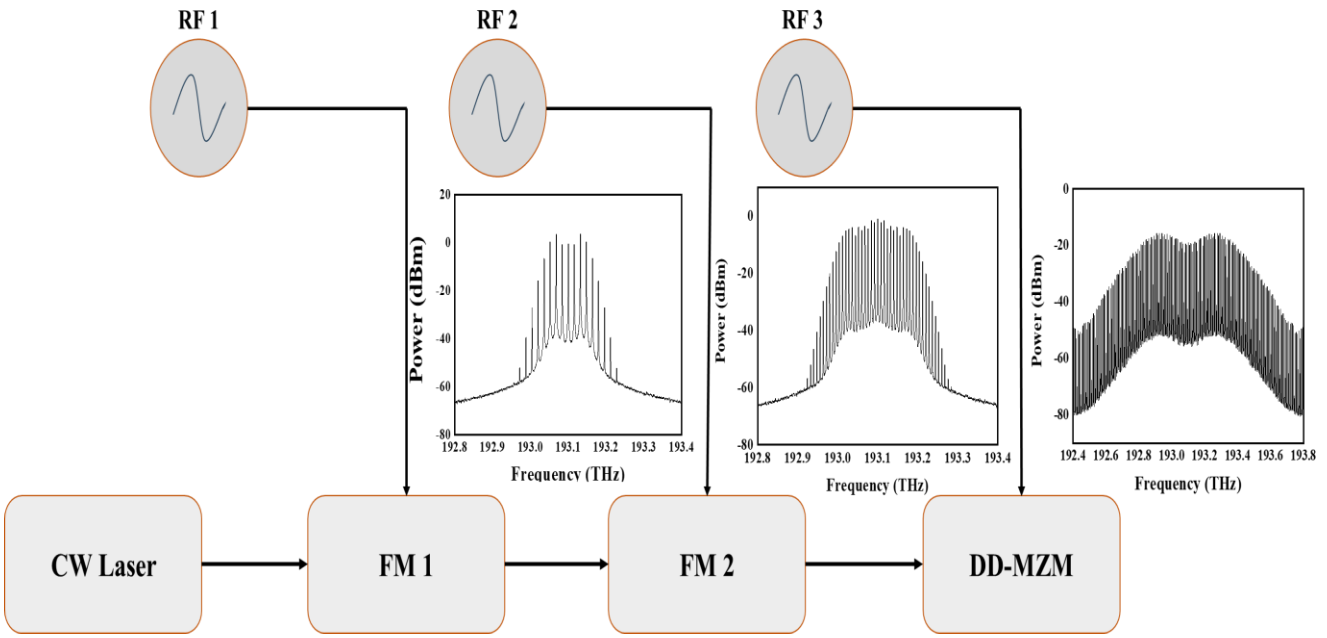

Fig. 1. Proposed setup to genetate OFC includes CW: continuous wave Laser, FM: Frequency Modulator, DD-MZM: dual drive-Mach Zehnder modulator

Table 1. Optimized parameter for generated Optical Frequency Comb

S. No	Component	Parameter	Unit	Value
1	CW Laser	Frequency	*THz*	193.1
		Power	*dBm*	10
		Linewidth	*MHz*	10
2	FM_1	RF Frequency	*GHz*	16
		Phase shift	*degree*	90
3	FM_2	RF frequency	*GHz*	8
		Phase shift	*degree*	45
4	DD-MZM	Bias voltage 1	*V*	-3.42
		Bias voltage 2	*V*	-2.368
		Modulation voltage	*V*	10
		RF Frequency	*GHz*	32
		Electrical amplifier	*dB*	10
		Phase shift	*degree*	90

3. Results and discussion

The performance of optical network design for OFC generation is analysed theoretically and analytically on basis of bias voltage applied across DD-MZM modulator. The obtained spectrum is analysed on optical spectrum analyser (OSA). The incoming electric field of laser is illustrated in equation (1)

$$E_c(t) = B_0 e^{j2\pi f_c t} \tag{1}$$

In equation (1), B_o and f_c represents amplitude and frequency of incoming source respectively. The output of laser followed by FM_I modulator which have optical as well as electrical input. The optical input coming from the output of laser source whereas the electrical input is driven by RF souce applied across modulator. The FM_1 output can be given in equation (2)

$$E_{fm1}(t) = B_0 e^{j2\pi f_c t} e^{j\beta_1 cos 2\pi f_1 t} \tag{2}$$

Whereas modulation index is denoted by β_1 and RF driving frequency of modulator is represented as f_1. The spectrum at FM_1 is given in Fig. 2 which depicts even and odd number of sidebands having 12 optical comb lines which is very less in number with 30 dB maximum power deviation. To maximize the optical frequency lines, output of FM_1 is followed by FM_2.

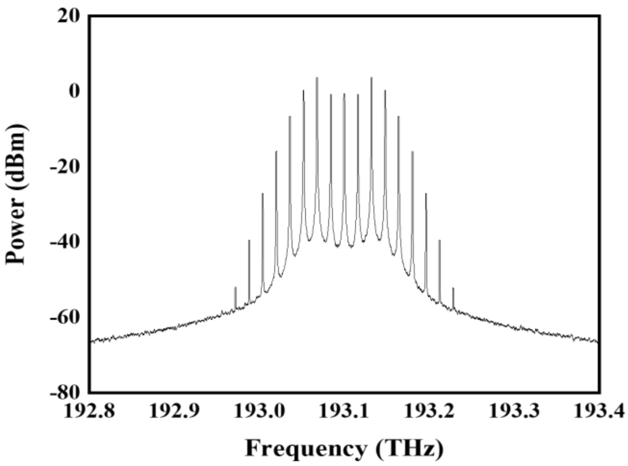

Fig. 2. The obtained OFC optical spectrum at output FM_1

The output optical field at FM_2 is depicted in equation (3) and equation (4)

$$E_{fm2}(t) = B_0 e^{j2\pi f_c t} T_{FM1} e^{j\beta_2 \cos 2\pi f_2 t} \tag{3}$$

$$E_{fm2}(t) = B_0 e^{j2\pi f_c t} T_{FM_{net}} \tag{4}$$

In equation (3) β_2 represents FM_2 modulation index whereas f_2 denotes RF signal frequency of FM_2. The transmittance of FM_1 is given by T_{FM1} whereas net transmittance of both FM is represented by $T_{FM_{net}} = T_{FM1}.e^{j\beta_2 \cos 2\pi f_2 t}$. The output spectrum of FM_2 is illustrated in Fig. 3. OFC generator at this stage produces 25 optical comb lines having 8 dB maximum power deviation. To increase the flatness of generated comb and to maximize number of subcarriers the output get applied to DD-MZM. The input of DD-MZM is fed by output of FM_2. Whereas RF signal applied across the MZM is 32 GHz.

The optical field at output of DD-MZM which is driven by RF sinusoidal signal $V_{MZM}(t) = V_m \cos 2\pi f_3 t$ is given by equations (5), (6) and (7)

$$E_{MZM}(t) = \frac{1}{2} E_{fm2}(t) \left[\exp\left(j\pi \frac{V_{MZM} + V_{dc}}{2} \right) + \exp\left(-j\pi \frac{V_{MZM} + V_{dc}}{V_\pi} \right) \right] \tag{5}$$

$$E_{MZM}(t) = E_{fm2}(t) \cos\left(\pi \frac{V_{MZM}}{V_{dc}} + \pi \frac{V_{dc}}{V_\pi} \right) \tag{6}$$

$$E_{MZM}(t) = B_0 e^{j2\pi f_c t} T_{FM_{net}} \cos\left(\pi \frac{V_m \cos 2\pi f_3 t}{V_{dc}} + \pi \frac{V_{dc}}{V_\pi} \right) \tag{7}$$

In above mentioned equations V_m, V_{dc}, V_π represents RF signal driving voltage, bias voltage of DD-MZM and half wave voltage of DD-MZM respectively. whereas $E_{fm2}(t)$ represents output of FM_2 which is represented in equation (4) [31].

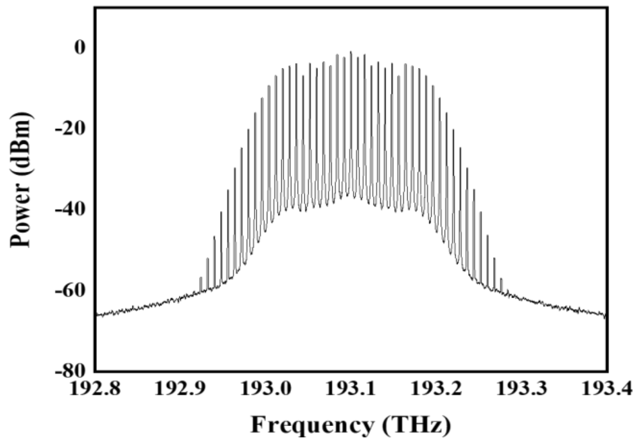

Fig. 3. The obtained OFC spectrum at output of FM_2

The DD-MZM output is denoted with Jacobi-Anger expansion which is given by equation (8).

$$e^{jx\cos\theta} = \sum_{n=-\infty}^{\infty} j^n J_n(x) e^{jn\theta} \tag{8}$$

$E_{MZM}(t)$ can be expand using Bessel function of first kind [32] which is represented in equation (9)

$$E_{MZM}(t) = T_{FM_{net}} \begin{pmatrix} B_0 \cos\varphi \sum_{n=-\infty}^{\infty} (-1)^n J_{2n}(b_1) \exp\left(j2\pi f_c t + j2n.2\pi f_3 t \right) - \\ B_1 \sin\varphi \sum_{n=-\infty}^{\infty} (-1)^n J_{2n+1}(b_1) \exp\left(j2\pi f_c t + j(2n+1).2\pi f_3 t \right) \end{pmatrix} \tag{9}$$

whereas $J_n(\beta_1)$, b_1, φ represents n[th] order bessel function of first kind, modulation index and phase produced by dc bias voltage respectively.

$$b_1 = \frac{\pi V_m}{V_\pi} \tag{10}$$

$$\varphi = \frac{\pi V_{dc}}{V_\pi} \tag{11}$$

The DD-MZM output by using Jacobi-Anger expansion is given by equation (12).

$$E_{MZM}(t) = \sum_{n=-\infty}^{\infty} J_n(\beta_1) e^{jn2\pi f_1 t} \times \sum_{n=-\infty}^{\infty} J_n(\beta_2) e^{jn2\pi f_2 t} \times \begin{pmatrix} B_0 \cos\varphi \sum_{n=-\infty}^{\infty} (-1)^n J_{2n}(b_1) \exp\left(j2\pi f_c t + j2n.2\pi f_3 t \right) - \\ B_1 \sin\varphi \sum_{n=-\infty}^{\infty} (-1)^n J_{2n+1}(b_1) \exp\left(j2\pi f_c t + j(2n+1).2\pi f_3 t \right) \end{pmatrix} \tag{12}$$

The above-mentioned equation (12) can be reduced to equation (13) which is given as

$$E_{MZM}(t) = \begin{bmatrix} J_1(\beta_1) e^{j2\pi f_1 t} - J_1(\beta_1) e^{-j2\pi f_1 t} + \\ J_2(\beta_1) e^{j2\pi (2 f_1) t} + J_2(\beta_1) e^{-j2\pi (2 f_1) t} + ... \end{bmatrix} \times \begin{bmatrix} J_1(\beta_2) e^{j2\pi f_2 t} - J_1(\beta_2) e^{-j2\pi f_1 t} + \\ J_2(\beta_2) e^{j2\pi (2 f_2) t} + J_2(\beta_2) e^{-j2\pi (2 f_2) t} + ... \end{bmatrix} \times \begin{pmatrix} B_0 \cos\varphi \sum_{n=-\infty}^{\infty} (-1)^n J_{2n}(b_1) \exp\left(j2\pi f_c t + j2n.2\pi f_3 t \right) - \\ B_1 \sin\varphi \sum_{n=-\infty}^{\infty} (-1)^n J_{2n+1}(b_1) \exp\left(j2\pi f_c t + j(2n+1).2\pi f_3 t \right) \end{pmatrix} \tag{13}$$

Whereas equation (13) depicts the final output which is generated at output of DD-MZM.

The performance of generated OFC can also analysed on basis of applied bias voltage across MZM modulator. The bias voltage is iterative over the range -5 V to 5 V. when voltage is -4.47 V, -3.42 V, -2.89 V and -2.36 V the produced optical comb lines is 69,60,81 and 55 with power deviation 6 dB, 2 dB, 1.5 dB and 8 dB respectively. The spectrum of optical frequency comb lines is more flat and broad at -4.47 V as compared to -2.36 V. This analysis is illustrated in Fig. 4. The output spectrum is illustrated in Fig. 5. which shows 81 optical frequency comb lines with 0.2 dB to 1.5 dB flatness and this setup of frequency comb occupies 852 GHz bandwidth with 4 GHz spacing between adjacent comb lines.

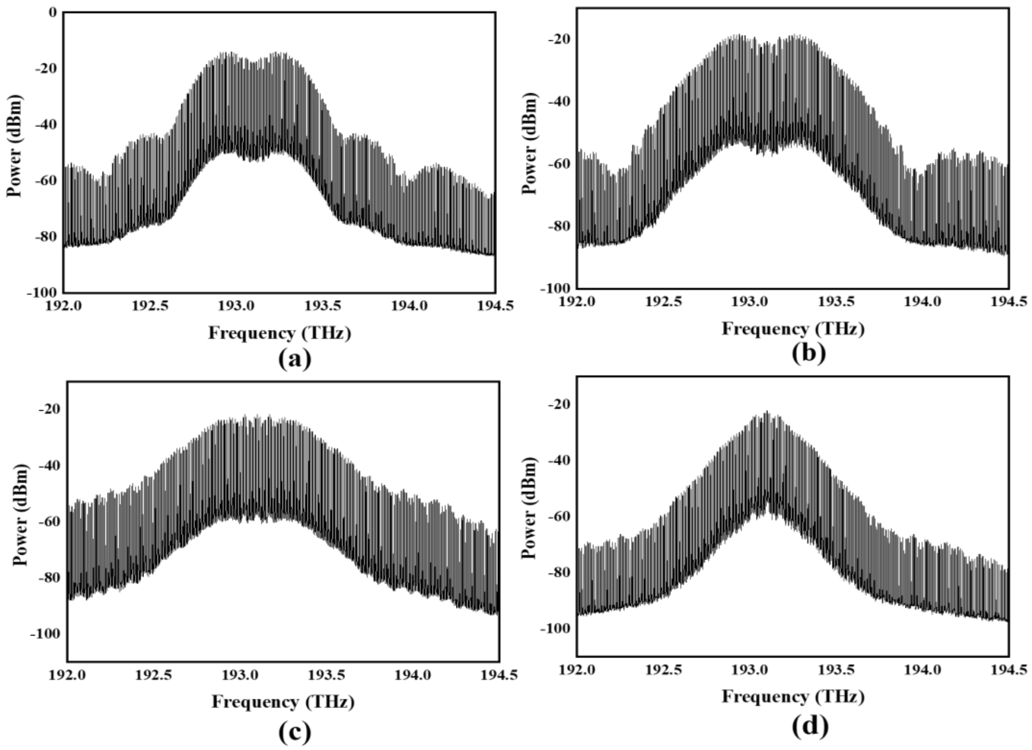

Fig. 4. Performance analysis based on applied bias voltage (V) (a) -4.47 V (b) -3.42 V (c) -2.89 V (d) -2.36 V

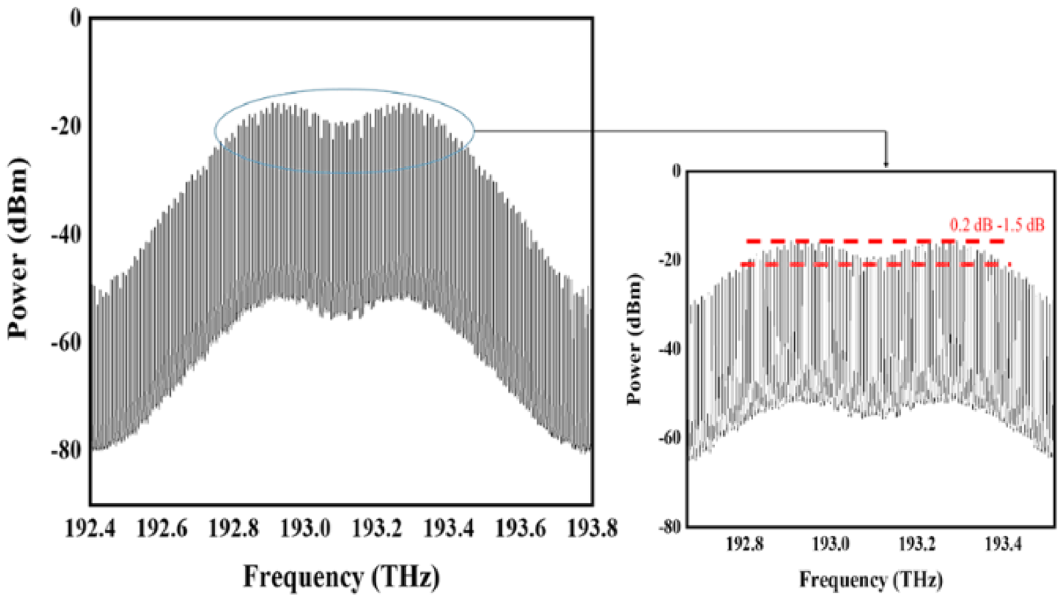

Fig. 5. Optical frequency comb generator (color online)

4. Conclusion

This manuscript presents an approach to produce optical frequency comb generator which is designed by employing DD-MZM at 32 GHz with Frequency modulators FM_1 at 16 GHz and FM_2 at 8 GHz respectively. Initially comb lines produced by FM_1 is less in number with less flatness than cascading of another Frequency modulator FM_2 is employed which act as subcarrier booster. At output of FM_2 OFC generator produces 25 comb lines with 8 dB flatness. To reduce the maximum power deviation as well to introduce the large number of optical carriers DD-MZM is introduced in setup of OFC generator. The OFC generator is able to generate 81 frequency comb lines with 0.2 dB to 1.5 dB flatness and having bandwidth of 852 GHz. The performance of generated frequency comb is also analysed with biasing voltage applied across the DD-MZM. The optical spectrum corresponding to applied biasing voltage illustrates the produced optical comb lines with maximum power deviation. This setup is proficient in field of optical communication, photonics as well as quantum optics.

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