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Optical Frequency Comb Sources: Some Recent Developments

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Abstract
An optical frequency comb is a multi-wavelength light source that consists of a sequence of discrete, equally spaced spectral lines which acts like a 'ruler' of light. Optical Frequency Comb Sources have enabled significant applications in the field of Optical Communications, Astronomical Observations, Microwave Signal Generation, High Resolution Spectroscopy, Meteorology, etc. Such a diverse set of applications has motivated various researchers to develop and explore various source generation techniques. Some popular optical comb source architectures include: 1) Mode Locked Laser based comb sources, 2) Modulator based comb sources, 3) Dual Source induced Four Wave Mixing in HNLFs/DSFs based comb sources, Stimulated Brillouin Scattering based comb Sources etc. In this paper we present a review of recent developments happening in the field of optical comb source implementations.

Keywords: Optical Frequency Combs, Four-Wave Mixing (FWM), Stimulated Brillouin Scattering (SBS), Wavelength Division Multiplexing, Non-linear Optics.

Introduction
In past recent years, we have witnessed a lot of research in the field of Optical Frequency Comb Sources (OFCs). OFCs have enabled significant applications in the field of Optical Communications, Astronomical Observations, Microwave Signal Generation, High Resolution Spectroscopy, Meteorology, Terahertz Communication etc. [1, 2, 3]. Earlier, the OFCs were designed based on mode locked lasers (MLLs) technologies [3, 4], but they lack certain features which demand further research in development of new methodologies for OFCs. MLLs are prone to number of limitations such as fixed comb spacing, power efficiency, flatness issues, less stability, more cost and complexity etc. [2, 3]. Researchers have been able to overcome some limitations; however, it is still challenging to attain certain desirable properties such as broad and flat spectra, high stability, tunability, reduced power consumption, managed dispersion etc. [5].

Multiple architectures of OFCs have emerged due to different sets of operational requirements, which motivated a number of researchers to develop following strategies: 1) Mode Locked Laser (MLLs) [3, 4], 2) Modulator based generation of Optical Combs Sources [6, 7], 3) non-linearity-based technique involving Four Wave mixing (FWM) in highly nonlinear fibers (HNLFs) [8, 9], 4) Stimulated Brillouin Scattering often known as 'SBS' technique [10] etc. In this paper, we further discuss the OFCs generation, its methods, types and their implementations.

The remainder of the paper is organized as follows: Section 2 is related to architectures of optical frequency combs. Section 3 describes literature survey in the form of a table and a brief discussion, while paper is concluded in section 4.

2. Architecture of Optical Frequency Combs Technologies
In this section, we describe operational principle of following OFC strategies: 1) Mode Locked Laser (MLLs) [3], 2) Modulators based generation of Optical Combs Sources [5, 6], 3) non-linearity-based comb source generation involving four waves mixing in highly nonlinear fibers (HNLFs) [8, 9], and 4) Stimulated Brillouin Scattering (SBS) based OFC generation [10].

Mode locking is a technique in which a laser is used to generate train of pulses with width of pulses varying from picoseconds to femtoseconds. It involves maintaining a fixed relationship between the longitudinal modes of the laser's resonant cavity [13]. Mode locking results with the requirement of mechanism that yields higher net gain for short pulses in comparison to Continuous Wave (CW) lasers [13]. The Active mode-locking is achievable if the periodic modulation of the resonator takes multiple round-trip times [14]. A train of very short coherent pulses generated by MLLs generates spectra of equally spaced discrete modes at a rate equal to transit times. A well-defined maintained phase relationship among several axial modes in the laser cavity generates output of very short pulses [12, 15].

A schematic diagram of passive mode locking technique is shown in Figure 1 where the phase relationship is enforced by an intra cavity, loss element and a Saturable absorber [15].

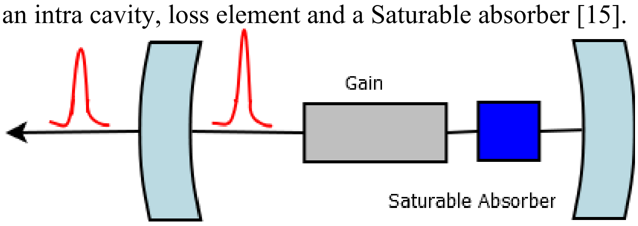

Figure 1. A Schematic Diagram of Passive Mode-locking Technique [12, 15]

Some applications of MLL based comb sources reported previously are Spectroscopy, Sensing, Phase Sensitive Amplifiers, Atomic Clocks, Optical Communications etc. [16, 17].

2.1 Modulators Based OFCs Generation

Previously, we observed that in generating optical frequency combs with the help of mode locked lasers [13], there are still certain limitations like precision, fixed frequency etc. To overcome these limitations, new techniques based on electro optical modulation were proposed in which a continuous optical wave from a frequency tunable laser is modulated using single or multiple modulators (phase/intensity based) [18, 19].

There are multiple variations of generating comb sources based on usage of modulators such as: i.) Single Phase Modulator (PM), ii.) Single Drive Intensity Modulator (IM), iii.) Dual Drive Intensity Modulator, iv.) Cascaded Modulators (PM or IM based).

The single-phase modulator-based comb source generation in schematic diagram shown in Figure 2, where the CW laser wave is injected into a phase modulator driven by Radio frequency RF Oscillator which produces sidebands at the output. The generated sidebands phase modulated by light contains several spectral components. The central frequency is determined by the seed continuous Wave (CW) laser source and the comb spacing between the side spectral components are defined by oscillator frequencies. But the generation of wide bands requires large modulation index, means a phase modulator should be used which has low half wave voltage V_π and ability to maintain a high RF voltage. This can be also attained either by cascading modulators as shown in Figure 3 or adding HNLFs as spectrum expanders [19].

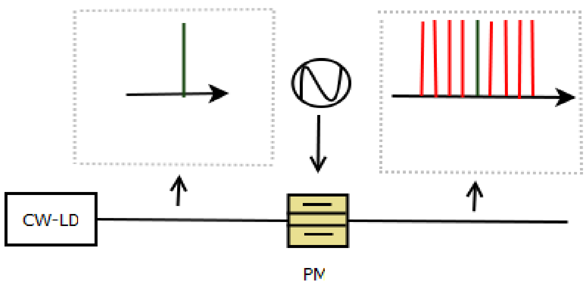

Figure 2. A Schematic Diagram of EOM based Comb Generation [19]

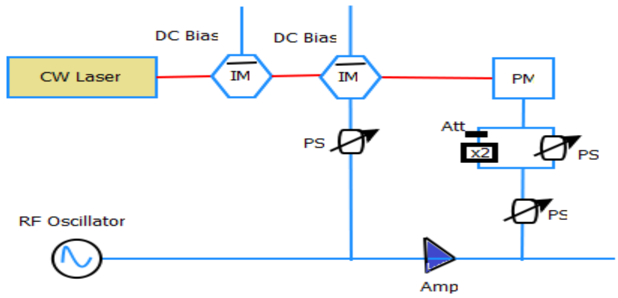

Figure 3. A Schematic Diagram of Cascaded Modulation Technique (IM and PM) [18]

Further details regarding other modulator-based comb sources can be referred in [6, 7, 17, 20]. Some applications of Modulator based comb sources reported previously are Terahertz Wave Generation, Sensing, Meteorology etc. [6, 17, 20].

2.3 Non-Linearity Based OFCs Generation

In the approach as shown in Figure 4, two CW laser seed sources of slightly different wavelengths have been used to initiate the chirp compression mixing process, which are fed into EDFA for amplification and then sent to the first stage of HNLF to induce a chirp and initiate a limited multi tone generation [19]. The chirped waveform is compressed by SMF to enhance the peak power. Further, the high peaked compressed waveform enters the last stage of HNLF where multitudes of higher order tones are generated by the process of FWM. By this way, adding more compression cycles and multiple chirp compression mixer stages, more comb modes can be generated depending upon the applications [19].

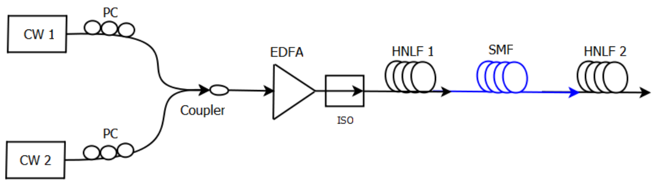

Figure 4. A Schematic Diagram of Non-Linearity based Comb Source Generation [19]

Two uniformly spaced lines used acts as both degenerate and non-degenerate pump waves mixed with input signal in generation of multitude of idlers which shows the replicated wavelength channels which is given by the relation as $n = 4m - 3$ where 'm' is the number of comb lines used in four wave mixing process and 'n' is the number of generated replicas [19]. In generation of these replicated carriers, there exist multiple FWM pathways, the frequencies of three uniform spaced pump waves have been denoted as $\omega_{1,}$ ω_2, $\omega_{3,} and\ \omega_{s,}$ respectively [19]. Each newly generated comb lines can be denoted as $\omega_{ijk} = \omega_i + \omega_j - \omega_k$. Here, i, j, k are the waves present during FWM process. The simultaneous spectral phase of the Four Wave Mixing 'FWM' is denoted by $\varphi_{ijk} = \varphi_i + \varphi_j - \varphi_k$, where $\varphi_i, \varphi_j, \varphi_k$ are the spectral phases of the three waves involved in FWM [19].

Some applications of non-linearity-based comb sources reported previously are Frequency Multiplication, Waveform Generation, Data Transmission, etc. [8, 9, 10].

2.4 Stimulated Brillouin Scattering (SBS) Based OFCs Generation

The basic principle of generation of OFCs based on SBS involves a fiber ring cavity, which is shown in Figure 5. A tunable laser source (TLS) which serve as the Brillouin Pump (BP) signal, a bidirectional EDFA, two optical circulators (to ensure the oscillation of the optical comb is in one direction only), two wavelengths selective couplers (WSCs) are used as to multiplex the BP and the signal waves, a coupler, with HNLF (Mode Fiber) is being used, where optical comb is being pumped by TLS [21]. SBS excites when the intensity of the BP signal is strong enough. The simultaneous existence of stokes within the ring cavity induces stokes and anti-stokes via the process of FWM inside the fiber [21].

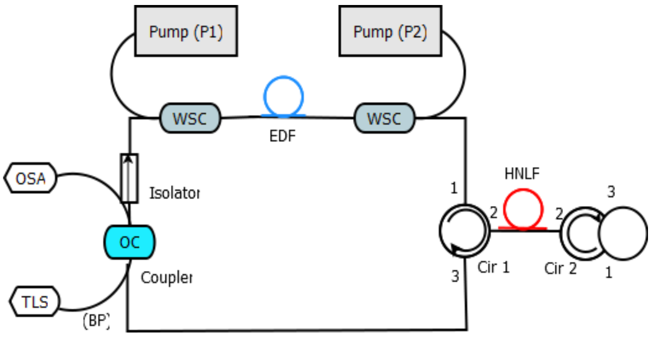

Figure 5. A Schematic Diagram of SBS Technique [21]

In the schematic diagram shown in Figure 5, the key operating principle here is half of the input power is pre-amplified which enters the HNLF. The optical resonator (cavity) consists of an optical coupler, an isolator, circulators (Cir 1 and Cir 2), a HNLF, two wavelength selective couplers and a bidirectional EDFA. The pump lasers are divided into two parts P1 and P2, by the coupler which is used to improve the amplifier's performance. Two WSCs are used to combine the Brillouin and signal waves as discussed above. The (TLS) enters the fiber's cavity as a (BP) signal via the optical coupler in the clockwise direction. The circulator 1 here works to provide a one directional path for both of the signals (BP and Brillouin Stokes (BS)), while the circulator 2 works as an optical mirror to reflect the (BP and BS) signals and forming a laser cavity. When the intensity of the entered waves (through circulator 1) is strong to trigger the SBS to happen, the resultant BS signals generated will flow in the opposite direction of BP signals. These signals will be reflected back to the HNLF via circulator 2. Now, these first order generated BS signals being amplified by EDFA with the help of BP Signals will again create the new signals which are of second order and the process repeats in the next cycle. But at the same time, the circulator 2 starts permitting BP and BS Signals propagating oppositely in the clockwise direction. Therefore, the degenerated and non-degenerated FWM processes happen [21]. Mathematically, when input of BP signal with frequency of ω_p which generates BS Signal of ω_s w.r.t the BP signal is given by $\omega_s = \omega_p - \Delta_B$ (shifted by Δ_B). These two waves interact and generate stokes signals of $(\omega_{i2} = 2\omega_s - \omega_p = \omega_p - 2\Delta_B)$ and anti-stokes signals $(\omega_{i1} = 2\omega_p - \omega_s = \omega_p + \Delta_B)$ with the help of the FWM process. Hence, in this way, generation of stokes and anti stokes of higher order are made with the help of cascaded SBS and FWM processes [21]. Some applications of SBS based comb sources reported previously are Dual Comb Spectroscopy, Optical Fourier Analysis, Generation of Chirped Waveforms, Spectral Shaping etc. [9, 21, 22].

3. Analysis and Discussions

A comparative survey of different OFC strategies based on following: 1) Mode Locked Laser (MLLs) [3, 4], 2) Modulator based generation of Optical Combs Sources [6, 7], 3) non-linearity-based technique involving Four Wave mixing (FWM) in highly nonlinear fibers (HNLFs) [8, 9, 18, 19], 4) Stimulated Brillouin Scattering [10, 21, 22] has been carried out and is shown in Table 1.

Table1. A Comparison between various OFCs generation techniques

Authors Name and Year	**Technique Used**	**Sub Techniques**	**No. of Comb Lines**	**Flatness**	**Power (dBm)**	**Applications**
Bagheri, et al [12] (2017)	MLL	Passive mode locking	120	-	>50 µW	Optical communications Signal Generation 3. Precise Waveform Shaping
E. Sooudi, et al [11], (2012)	MLL	Active mode locking	11-35	Within 10 dB	330 µW	Terahertz Wave Generation High Accuracy 3. Optical Communications
Y. Dou, et al [20] (2012)	Modulators	Electro Optic Modulation	29	<1.5 dB	.9 m W	Optical communications 2. Signal Generation Precise Waveform Shaping
I.Morohashi, et al [6] (2012)	Modulators	Dual Drive MZM	35	10 dB	.9 m W	1. Terahertz Wave Generation 2. High Accuracy 3. Optical Communications
H. Sun [23] (2021)	Modulators	Electro Optic Modulation	11	3 dB	-	Nyquist WDM Transmission Signal Processing applications 3.Precision Distance Measurements 4.Optical Communications
R. L. Ferreira, et al [7] (2013)	Modulators	Cascaded Modulation	10	-	1.259 mW	High-Capacity Optical Communications Comb Generator 3.Super channel

T. Ren, et al [24] (2019)	Modulator	Single PM	>40	-	10 dB	Photonics and Microwave Systems Temporal Imaging Systems EO Combs
A Wiberg, et al [9] (2006)	Non-Linearity	FWM	2 Idler tones at +3f and -3f	-	94 W	Frequency Multiplication Multimeter Wave Generation Data Transmission Microwave Photonics
B. M. Anderson, et al [10] (2017)	Non-Linearity	SBS	128	<2 dB	330 W	Non-Linear Mitigation Coherence Arbitrary Waveform generator
J. Tang [21] (2011)	Non-Linearity	SBS and FWM	150	12dBm	165 mW	Optical Communications Optical Testing and Measurements Microwave Photonic Systems

As shown in Table 1. It has been observed that different types of applications require different set of requirements. For e.g., Applications like frequency multiplication, precision measurements, microwave photonics etc., OFC generation techniques based on 'non linearity' is highly suitable and we found out that the maximum number of comb lines can be generated are upto 150. Furthermore, for applications like mid IR Spectroscopy, techniques based on mode locking (Passive MLL), are suitable which can generate upto 120 comb lines. Thus, for a particular application, an OFC generation technique can be suitable which satisfies precise parameters required by target application.

4. Conclusion

In this paper, we have reviewed the different techniques for generation of OFCs. We have analyzed and compared different aspects of the OFCs sources such as number of comb lines, power, flatness, etc. We also studied the possible applications for different OFC generation methods as each one requires different sets of parameters as discussed above by utilizing various sub techniques like modulator based, non-linearity based, SBS etc., depending on the application targeted.

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