# Photonic Mixer Incorporating All-Optical Microwave Frequency Generator Based on Stimulated Brillouin Scattering Using Single Laser Source

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**ABSTRACT** In this paper, we report the theoretical and experimental implementation of a photonic mixer for Radio-Over-Fiber (RoF) transmission systems, which incorporates an all-optical 10.87 GHz microwave frequency signal generator based on beating laser frequency with its first order Stimulated Brillouin Scattering (SBS) frequency shift. A 13GHz Radio Frequency (RF) is down-converted to 2.13 GHz Intermediate Frequency (IF) signal. The proposed system configuration represents a cost-effective photonic mixer that can be deployed for up and down conversion around 11 GHz in RoF transmission systems. The optically generated microwave signal of 10.87 GHz has a phase noise of $-109$ dBc/Hz at 15-MHz offset. The proposed photonic mixer exhibits a Spurious-Free Dynamic Range (SFDR) of 93dB.Hz$^{2/3}$. This RoF transmission system configuration deploys dual parallel Gallium Arsenide (GaAs) Mach Zehnder Modulator as a photonic mixer, and a single laser source as a Brillouin pump and as an optical carrier at the same time. To the best of our knowledge, this type of photonic mixers has not been reported in the literature.

**INDEX TERMS** Radio-over-fiber (RoF), stimulated Brillouin scattering (SBS), dual parallel Mach Zehnder modulator (DPMZM), Brillouin selective sideband amplification (BSSA), carrier suppressed single side band (CS-SSB).

## I. INTRODUCTION

Microwave photonics brings together the world of Radio Frequency (RF) engineering and optoelectronics [1]–[3]. The limitation of microwave signal processing such as lack of configurability, limited bandwidth, high energy consumption, prone to electromagnetic noise and interferences can be circumvented through microwave photonics, which refers to the processing of RF signals in the optical domain [4], [5]. Main advantages that fiber communication systems offer are; low electromagnetic interference, extremely low losses, better security and huge bandwidth capacity [5], [6].

Microwave signal processing in radar and wireless communication systems involve frequency mixing, where incoming high frequency RF signal, from an antenna, is mixed with Local Oscillator (LO) signal by an RF mixer and then down-converted to a lower Intermediate Frequency (IF) signal. The down-converted IF can be processed further by deploying low-speed electronic circuitry to recover the baseband signal. In this regard, photonic mixers have potentially game changing features when compared to electronic mixers. Photonic mixers offer extensive operational bandwidth, near infinite isolation between the RF and the LO ports, and Electromagnetic Interference (EMI) Immunity, which are unique fundamental features of photonics technology [7].

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Currently, most common photonic mixer structures are based on two Lithium Niobate (LiNbO$_3$) Electro-optic intensity modulators connected in series [8], and LiNbO3 integrated Dual Parallel Mach Zehnder Modulator (DPMZM) with integrated optical phase shifter [9], [10]. However, in our proposed RoF system, we have used Gallium Arsenide (GaAs) integrated DPMZM as a photonic mixer which has an excellent capability in managing RF signals in space, aerospace and satellite-to-ground downlink communication systems. The proposed photonic mixer deploys Stimulated Brillouin Scattering (SBS) frequency shift. It is known that SBS causes system degradations in fiber-optic networks [11], [12]. However, SBS can also have major beneficial characteristics for microwave photonic signal processing such as frequency selective amplification, specific loss spectrum (suppression) and Brillouin Stokes frequency shift. Among these major beneficiaries is the Brillouin Selective Side Band Amplification (BSSA). The BSSA has been used to achieve a gain in microwave photonic mixing [13], [14]. It has also been used to achieve Single Sideband modulation (SSB) of 11-GHz RoF system [15]. Brillouin carrier suppression technique is also used to achieve high conversion efficiency in microwave photonic mixer [16]. Furthermore, BSSA has been exploited in opto-electronic oscillator (OEO) as a very high Q narrow-band optical filter to selectively amplify oscillation mode [17]–[20]. In this study, we have used SBS for microwave frequency generation.

Microwave frequency generation occurs by heterodyning the input laser and its second order Brillouin Stokes signal through the circulation/isolation of its first order Stokes signal in optical fiber has been reported in [21]. Brillouin scattering Stoke frequency shift in Single Mode Fiber (SMF) is reported in [22], where two-frequency Brillouin fiber laser is used as an optical microwave generator. However, none of the above stated literature evaluated the performance of all-optical microwave signal generation for microwave photonic mixing. Furthermore, in ref. [21] and [22], they require two independent lasers to generate RF signal optically and provide an optical carrier to microwave photonic mixer, which is more expensive and adds the complexity to the RoF transmission systems.

In this study, we have proposed a novel photonic mixer structure configuration using Gallium arsenide (GaAs) DPMZM incorporating 11-GHz all-optical microwave signal generator by heterodyning input laser and its first order Brillouin Stokes. A single laser source is used as a Brillouin pump and provide the optical carrier for the DPMZM. The GaAs structures are traditionally the material of choice for designing photonic devices that operate at millimeter-wave frequencies, due to the availability of low-loss, semiconductor integration conveniences, and high resistivity substrate. Furthermore, characteristics of environmental stability, including a reasonable degree of radiation hardness make GaAs material structures ideal for systems which must survive and operate in harsh environment such as space and defense sectors [23].

## II. THEORY AND OPERATION PRINCIPLE

Light scattering in optical fiber is omnipresent regardless of the amount of optical power present in the fiber. There are two types of light scattering in optical fibers: spontaneous and stimulated scattering. In spontaneous scattering, the optical material constituting the optical fiber such as refractive index does not change due to the presence of the incident light wave (electromagnetic field). However, in the case of when a high power of incident light wave in lunched in the fiber, the spontaneous light scattering can become quite intense which causes changes the optical property of the material; this regime is known as SBS [24]. In other words, the SBS is an interaction between an intense optical field, a pump wave, and an induced electro strictive acoustic wave in the fiber. Due to the relative velocity interactions between the pump (incident light wave) and the acoustic wave, the backscattered wave is shifted in frequency [25]. The backscattered Brillouin frequency shift $V_{BS}$ is defined as [25]:

$$v_{BS} = \frac{2nV_a}{\lambda} \tag{1}$$

where $V_a$ is the acoustic velocity within the fibre, $n$ is the refractive index of the fibre, and $\lambda$ is the operating wavelength of the incident light wave. In the case of silica based optical fibres such as SMF-28, the Brillouin frequency shift is governed by the value of the acoustic velocity in silica $v_a = 5587$ m/s and refractive index $n = 1.46$. In silica based optical fibres, the Brillouin frequency shift is equal to the acoustic frequency which is around (9-11) GHz. The SBS threshold power is defined as [25]:

$$g_B K (P_{th}/A_{eff}) L_{eff} \cong 21 \tag{2}$$

where $g_B$ is the Brillouin gain coefficient of the material, $P_{th}$ is power corresponding to the Brillouin threshold, $A_{eff}$ is the effective cross-sectional of fiber, $L_{eff}$ is the effective length and $K$ is a constant that depends on the polarization property of the fiber, which is 1 if the polarization is maintained and 0.5 otherwise. Typical silica based SMF-28 fiber has Brillouin gain coefficient $g_B$ is $\left(4.40 \times 10^{-11}\right) \frac{m}{W}$. Modeling the effective length $L_{eff}$ is complicated. However, a simple model that assumes the signal power is constant over a certain effective length has proved to be useful in understanding the effects of the fiber nonlinearities. The effective length $L_{eff}$ is defined [21]:

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \tag{3}$$

where $\alpha$ is fiber attenuation per km, $L$ is the original fiber length. Typically, $\alpha = 0.22$ dB/km for SMF-28 fiber. In Fig. 1, we illustrate calculations of effective length as a function of fiber length in km. For 2km length of optical fiber, the calculated $L_{eff}$ is 1.61 km. It is worth stating that after 20 km, the effective length of a fiber is around 4.85 km, and it is constant regardless of the fiber length, as shown in Fig. 1. In our study, the effective cross section of the SMF fiber is
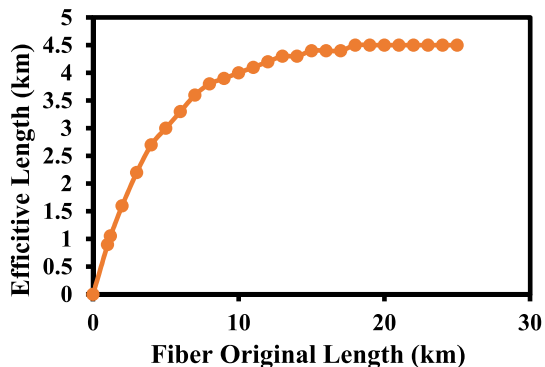
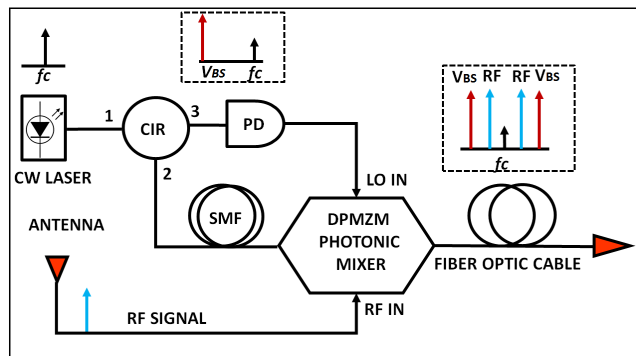**FIGURE 1.** Fiber original length and calculated effective length.



**FIGURE 2.** The schematic diagram of the proposed structure. CW: continuous wave laser; CIR: optical circulator; PD: photo detector; SMF: Single Mode fiber; DPMZM: Dual Parallel Mach Zehnder Modulator.

86.5 $\mu m^2$. The SBS threshold $P_{th}$ power is calculated based on the original fiber length of 2 km, using eq. (2).

$$g_B K (P_{th}/A_{eff}) L_{eff} \cong 21$$

$$P_{th} = \frac{21 \times A_{eff}}{K \times P_{th} \times L_{eff}}$$

$$P_{th} = \frac{21 \times 86.5 \mu m^2}{0.5 \times \left(4.40 \times 10^{-11}\right) \frac{m}{W} \times 1610 m}$$

$$P_{th} = \frac{21 \times 86.5 \mu}{0.5 \times \left(4.40 \times 10^{-11}\right) \times 1610} W$$

$$P_{th} = \frac{21 \times (86.5 \times 10^{-12})}{0.5 \times \left(4.40 \times 10^{-11}\right) \times 1610} W$$

$$P_{th} = 51.29 \, mW$$

According to the above calculation results, the SBS threshold power $P_{th}$ for 2 km optical fiber is 51.29 $mW$.

The schematic diagram of the proposed photonic mixer configuration is shown in Fig. 2. The laser source provides a continuous wave light into the DPMZM via the Optical Circulator (CIR) port 2 over a reel of the SMF. An ideal CIR should stop (completely isolate) optical signal propagating between port 1 and port 3, allowing the optical signal to propagate only between ports 1 and Port 2, and port 2 and port 3. However, in the practical implementation of such CIRs, there is always some optical signal leakage between port 1 and port 3. This
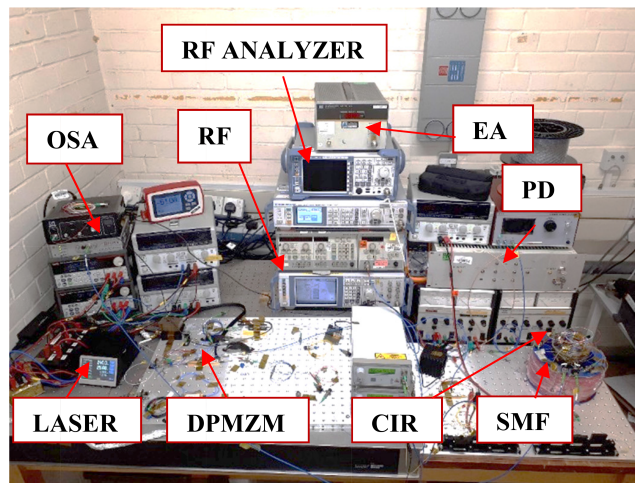


**FIGURE 3.** Experimental setup of the proposed structure.

allows some of the CW laser optical carrier signal $f_C$ to propagate towards the port 3 of the CIR. In this case, most of the laser light from port 2 is propagating through the SMF-28 reel. In our proposed schematics, the SMF-28 reel is used as a Brillouin gain medium where the counter-propagating Brillouin stokes gain is generated at the frequency $V_{BS}$, and it counter propagates towards port 2, and then to port 3.

At port 3, some of the CW laser signal leakage $f_C$, from port 1 is already propagated. Hence, both signals ($f_C$, from port 1, and Brillouin Stokes shift frequency $V_{BS}$, from port 2) are mixed at port 3 and beat together at the Photo Detector (PD) to generate high frequency microwave signal. The generated microwave signal is amplified by built-in Electric Amplifier (EA) inside the PD and fed into the DPMZM's Local Oscillator (LO) port. Light propagating from the other end of the SMF-28 reel is propagating via the Polarization Controller (PC) into the DPMZM. The PC is deployed to maintain the light polarization. As shown in Fig. 2, the upper arm of the DPMZM is modulated by the optically generated RF signal. The lower arm of the DPMZM is modulated by the RF signal from antenna [9]. Finally, both optical sideband $V_{BS}$ and applied RF are mixed optically at the DPMZM, then transmitted at the remote destination thought the optical fiber. At the receiver the RF signals are then processed further by deploying low speed and low power electronic systems.

## III. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental structure of the proposed photonic mixer configuration, illustrated in Fig. 2, is developed and implemented in Microwave Photonics and Sensors lab, shown in Fig. 3. This experimental set up shows the arrangement connections of photonic components and measurement equipment, including both microwave and optical spectrum analyzers. As an optical source, we used a laser operating at 1549.948 nm (193.421THz), with a narrow linewidth of 50 kHz (Thorlabs-SFL 1550 S) and optical power of 18 dBm, connected to the CIR (Thorlabs CIR1550SM) in port 1. The insertion loss of the CIR is 1 dB, whereas the
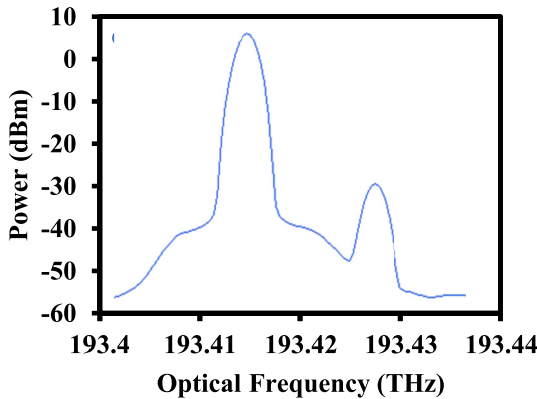
**FIGURE 4.** Optical spectrum measured at CIR port 3 shows Brillouin Stokes frequency shift ($V_{BS}$) at 193.411 THz and CW laser frequency at 193.421 THz imitating SC-SSB signal.



**FIGURE 5.** RF spectrum-phase noise of the 10.87 GHz generated microwave signal −109.20 dBc/Hz at 15 MHz offset.

isolation between port 1 and port 3 is 25 dB. Port-2 of the cir is connected at the one end of the 2 km SMF-28 fiber reel to generate the SBS.

Most of the CW laser light (18 dBm) from the port 2 is propagating through 2 km SMF. As explained in Fig. 2, the SMF-28 reel works as Brillouin gain medium, consequently, Brillouin Stokes frequency ($V_{BS}$) is generated and counter propagates towards the CIR port 2. The counter-propagating Brillouin frequency ($V_{BS}$) from port 2 and some light leakage from the CW laser signal $f_C$ at 1549.948 nm (192.421 THz) from port 1, are mixed at port 3, which operates like a Carrier Suppressed Single Side Band (CS-SSB) signal.

Variation of the optical frequency (THz) as a function of the measured power in dBm is illustrated in Fig. 4. This figure displays the optical spectrum measured at port 3,showing Brillouin Stokes frequency shift ($VB_S$) at 193.411 THz and the CW laser frequency at 193.421 THz, which is replicating the SC-SSB signal. Our experiment shows that the Brillouin Stokes frequency shift is observed at 1550.028 nm (193.411THz) with 5 dBm optical power. The linewidth of the SBS Stokes frequency is measured to be 10 MHz. It is worth stating that, the minimum achievable Brillouin first order stokes frequency linewidth is limited to 10MHz due to acoustic phonon lifetime in the silica based optical fiber. In Fig. 4, both stokes and the signal appear to be broader due to the resolution constraints of the Optical Spectrum Analyzer (OSA) used to measure the optical carrier. The resolution of our OSA is limited to 10 GHz. Moreover, the linewidth of Brillouin stokes frequency shift is measured by heterodyning laser signal frequency with stokes frequency signal at the photodetector. Our heterodyning measurement results show the linewidth of the Brillouin Strokes is 10 MHz, as shown in Fig. 5.

The CS-SSB signal from port 3 is sent to the PD (DSC-40s). The 3-dB bandwidth of the PD1 is 18 GHz with a responsivity of 0.80 A/W. The CS-SSB beats at the PD and generates 10.87 GHz microwave signal which is then fed into DPMZM LO port. The phase noise of the
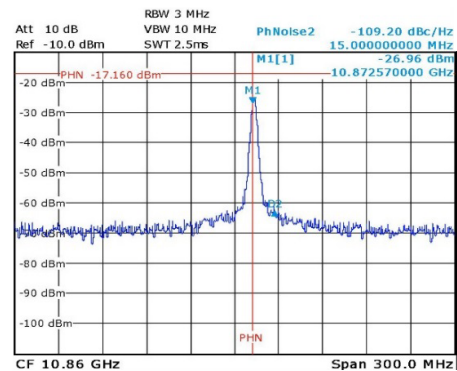
optically generated 10.87 GHz microwave signal is measured to be −109 dBc/Hz at 15 MHz offset using Rode and Schwarz-FSL RF spectrum analyzer, as shown in Fig. 5. The line shape of the generated heterodyning microwave signal is observed on the electronic spectrum analyzer is well matched with the Gaussian fitting curve shown in Fig. 6. The linewidth of the optically generated microwave signal is ∼10 MHz. This was measured by the heterodyne beating of the laser frequency with its first order (SBS) frequency shift on the PD, as shown in Fig. 5.

The generated 10.87 GHz microwave signal is amplified by 30 dB power amplifier built in the PD and then injected into the upper arm of the integrated DPMZM's LO port. A 13 GHz microwave signal is applied into the RF port of the DPMZM as an incoming RF signal. In this experiment, Gallium arsenide (GaAs) based Axenic -aXsd-2050) DPMZM are deployed due to their advantages in terms of harsh environment applications for radar and satellite communication systems.

The 3-dB bandwidth of the DPMZM is 50 GHz with the insertion loss of 10 dB. The half-wave voltage $V\pi$ for the child-1 and child-2 modulators are around 10 V-DC, and for the parent modulator $V\pi$ is 12 V-DC.

In such RoF transmission systems, it is necessary to suppress the carrier. Within this experiment, in order to minimize the carrier, we optimized the bias voltages of the DPMZM. Our measurements show that the optimized DPMZM bias voltages to minimize the carrier are at; $V_{b1} = 6.50$ V, $V_{b2} = 11.85$ V and $V_{b3} = 1.85$ V. These bias voltage values are proven to achieve a large carrier suppression of 45 dB, resulting in a down-converted IF signal of 2.13 GHz. The down-converted IF signal is measured at the remote destination.

Conversion efficiency as a function of input RF signal frequency of the proposed photonic mixer is shown in Fig. 7, It can be seen from the figure that the photonic mixer response between 2-16 GHz is almost flat around 1.5 dB variation. This conversion efficiency of the generated optical microwave signal is benchmarked with the commercial RF Source (Rode& Schwarz-SFL-100A), shown in Fig. 7.

As illustrated in the Fig.7, the generated RF source using in the proposed structure is very precise. This demonstrates
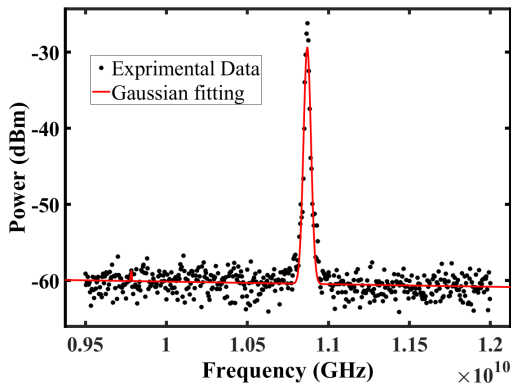
**FIGURE 6.** The Gaussian curve fitting result of the optically generated microwave signal.
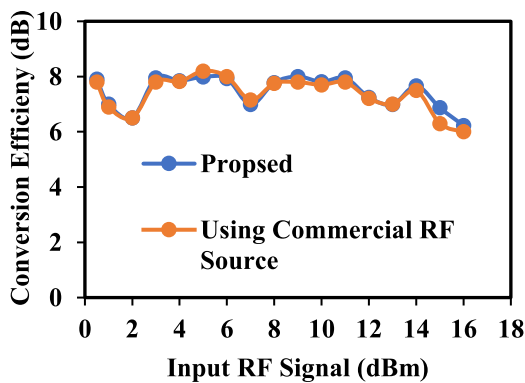


**FIGURE 7.** Measured conversion efficiency of the proposed DPMZM structure as a function of RF frequencies.
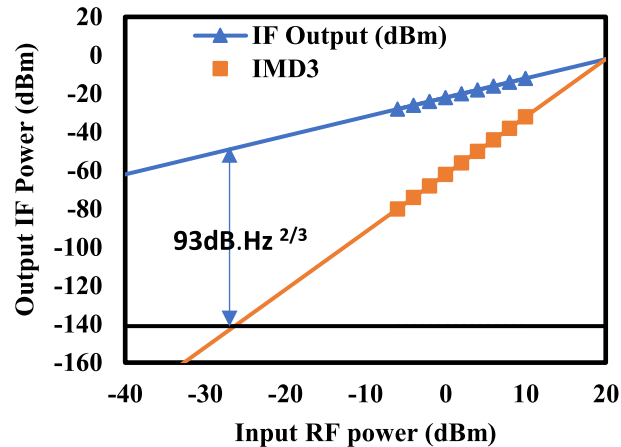


**FIGURE 8.** SFDR of the proposed photonic mixer.

minimum requirement of 72 dB.Hz $^{2/3}$ reported in Ref [26], and it also demonstrates a 3.5 dB SFDR improvement when compared to the reported SFDR in Ref. [14]. The proposed system configuration represents a cost-effective microwave photonic mixer that can be deployed for up and down conversion around in RoF transmission systems.

## IV. CONCLUSION

Throughout the experimental analysis, our data determines an innovative microwave photonic mixer, incorporating an-all optical 10.87 GHz microwave frequency generator. These have been projected on Brillouin Stokes utilizing a single laser source. To demonstrate the performance of the proposed optical mixing for $IMD_3$ measurement, two tones RF input signals at 13.00 GHz and 13.01GHz are down converted to $IF_1$ at 2.13 GHz and $IF_2$ at 2.14 GHz, respectively. The lower $IMD_3$ is measured at 2.12 Hz and upper $IMD_3$ is measured at 2.15 GHz. The measured phase noise of the optically generated microwave signal at 10.87 GHz is −109 dBc/Hz at 15MHz offset. The proposed analog configuration is used to down-convert the incoming RF signal whilst demonstrating high SFDR performance of 93dB.Hz$^{2/3}$ with low cost, low complexity while using a single laser as a carrier and for RF generation. This meets the minimum requirement of 72 dB.Hz $^{2/3}$ reported in Ref [26] and also demonstrated a 3.5 dB SFDR improvement when compared to the reported SFDR in Ref. [14]. We have developed and implemented a cost-effective microwave photonic mixer structure for RoF transmission systems, where the CW lasers are used as a Brillouin pump for generating the RF optically and as the optical carrier for the DPMZM, simultaneously. This new technique reduces the complexity of RoF transmission systems when deploying multiuser systems with ultra-high bandwidth capacities. The proposed photonic mixer has also been used to down-convert the incoming microwave signal. This new structure can also be used as an all-optical microwave photonic up converter for RoF and antenna remoting around 11 GHz. Future work will be on using this new technique at a higher frequency. To the best of our knowledge, these

the accuracy of our proposed DPMZM photonic mixer, where the conversion efficiency of the optically generated microwave signal and commercially available RF source are similar.

In addition to this, we have also investigated the dynamic range performance of the proposed RoF photonic mixer. The Spurious Free Dynamic Range (SFDR) measurement is carried out with two RF signal tones; 13.00 GHz ($RF_1$) and 13.01 GHz ($RF_2$), and they are fed to DPMZM RF electrodes. Our measurement shows that noise floor is −143.5 dBm/Hz. It is worth stating that during the SFDR measurements, third-order Intermodulation Distortion (IMD3) components at 2.12 GHz ($IMD_3$-Lower) and 2.15 GHz ($IMD_3$-Upper) are measured and calculated using the following equations;

$$IMD_3(Lower) = \{(2RF_1 - RF_2) - V_{BS}\} \qquad (4)$$

$$IMD_3(Upper) = \{(2RF_2 - RF_1) - V_{BS}\} \qquad (5)$$

where $RF_1$ is the first RF tone 13 GHz, and $RF_2$ is second RF tone 13.01 GHz, $V_{BS}$ is the optically generated RF signal at 10.87 GHz, which is fed into LO port of the DPMZM. Fig. 8 illustrates the fundamental signal and $IMD_3$ components. The SFDR of the proposed method is measured to be 93dB.Hz $^{2/3}$ for a given optical condition, which meets

types of photonic mixers have not been reported in the literature.

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