Dual-Wavelength Fiber-Laser-based Transmission of Millimeter waves for 5G-supported Radio-over-Fiber (RoF) links

Hani J. Kbashi, Vishal Sharma, and Sergey Sergeyev

***Abstract*—This work utilizes an experimentally designed erbium-doped fiber-based tunable dual-wavelength laser (*EDFL*) to generate phase-stable millimeter waves over a wide-band of ≈ 12-110 GHz and their transmission over the radio-over-fiber (*RoF*) link. The generated fiber-laser-based millimeter waves are transmitted over a *RoF* link, including an optical link of 20 km and a wireless link of 50 m, which is carried out via a co-simulation of *Optisystem*^{TM} and *MATLAB*^{TM} software. The successful transmission of the proposed fiber-laser-based millimeter waves show the possibilities of realizing diverse *5G*-supported microwave-photonic systems.**

***Index Terms*— Fiber lasers, Radio-over-fiber links, radio frequency photonics, tunable lasers, 5G**

I. INTRODUCTION

THE unprecedented demands for high-speed wireless access have been augmenting for providing high-speed broadband multi-media services over prolonged wireless links. The deployment of the existing wireless-links using micro-and pico-cell architecture proved to be expensive with having other link-issues, including congestion and atmospheric fluctuations. Alternatively, the use of millimeter-wave (*mmW*) bands for the realization of fifth-generation (*5G*) networks is gaining considerable attraction to meet the required demands of high-speed indoor- and outdoor- wireless services. For the deployment of *5G* technology, the mmW waves are sub-divided into two designated bands as mid-band and low-band. The low-band utilizes the same frequency range as the fourth-generation (*4G*) technology and offers a similar capacity. However, for 24 GHz-72 GHz, beyond the lower boundary of the EHF band (extremely high-frequency band), the covered area is less, which augments the need for a large number of cells and thus the number of antennas [1]. It further increases the cost of the system-infrastructure. Moreover, the link-fading due to severe atmospheric fluctuations in the mmW band limits the coverage area. The RoF technology, a versatile back- and front-haul architecture are gaining popularity for the last few years due to its potential to offer high-speed wireless access over an extended coverage area even in the presence of adverse environmental conditions [2]. The resources are shared among all the front-haul links to serve several macro-cell, micro-cell for outdoor coverage, and pico-cells for indoor applications at the central office. The central office is connected to a simple, low-cost radio access point (*RAP*) through an interference-resistant, high-capacity optical fiber. At the RAPs, the optical signals are transformed back to the radio frequencies and then radiated via an air interface after amplification [3]. Due to its centralized architecture, it is also convenient to upgrade the existing wireless services to adopt advanced signal processing methods and improve the wireless access in terms of data rate and reliability [4].

As per [5], the optical access networks need to be scalable to deploy 5G technology to provide ≈ 10 Gb/s at the user-end, 100 Gb/s at the back-haul links, 1 Tb/s for metro transport, and 1Pb/s for the core transport. Also, for the deployment of 5G-supported high-speed wireless access networks, several mmW bands including 28-30 GHz, 55-60 GHz, 71-76 GHz, 81-86 GHz, and 92-95 GHz are available to provide proficient spectrum-utilization together with a covert transmission that attracts the telecommunication-and intelligent transportation-industries [6-8]. However, the generation of mmW waves in the available bands using traditional electronics-based techniques is costly and less phase-stable. Moreover, these techniques usually are accompanied by some frequency-multipliers which offer low-power, low-efficiency, and high phase-noise. Alternatively, the high-power photonics-based millimeter wave-generation are more phase stable and simpler to realize.

Due to a cost-effective approach, the dual-wavelength fiber-lasers (DWFL) are attaining significant attention for the last few years in designing various integrated microwave-photonics systems like integrated microwave-photonics systems, intelligent transport systems, and light detection and ranging systems. In contrast to the earlier reported approaches [9-11], DWFL-based generated mmW waves are free from using any high-quality microwave source. It further reduces system complexity and cost considerably. Moreover, DWFL generates mmW signals with low phase-noise by beating two optical signals with a wavelength spacing analogous to the desired millimeter-wave [12]. In the last few years, many approaches for developing the *DWFL* lasers by incorporating a dual-wavelength-filter inside the laser-cavity have been demonstrated successfully [13-18]. However, achieving a

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phase-stable dual-wavelength laser output by employing an erbium-doped fiber laser (*EDFL*) in the 1.55 µm region at room temperature is a thought-provoking task due to strong mode-competition. The mode-competition is triggered due to the homogeneous gain-broadening in the *EDFL* laser. Many approaches have been reported to overcome the mode-competition problem [16-28] but result in an increased cost and designing-complexity. Moreover, these approaches require a high-quality tunable microwave reference source that compels to discover another economical alternative to generate phase-stable mmW signals.

On the other hand, the 55 GHz – 60 GHz band is used for sensing climate variations and for Wi-Fi-based applications. The 74-77 GHz frequency band is used for automotive target detection and ranging by Autonomous Vehicle (*AV*) industries for achieving high range-and velocity-resolution in contrast to the 24 GHz frequency band [29]. Moreover, the 71-76 GHz, 81-86 GHz, and 92-95 GHz frequency bands for deploying point-to-point high-bandwidth communication links are preferred [30]. The 40-70 GHz band is also gaining popularity in millimeter-wave therapy to examine the cell-growth variations, enzyme functions, and membrane activities [31]. Subsequently, the authors demonstrate a simple tunable dual-wavelength *EDFL* laser in a simple design to generate phase-stable mmW waves to implement a *5G*-supported microwave-photonics system over a wide range of ≈ 12-110 GHz in this work [32]. The proposed *EDFL* laser is designed experimentally using a high-birefringence fiber with two polarization controllers in a ring-structured laser-cavity. A controlled-tuning of laser-cavity generates stable mmW signals by adjusting its state-of-polarization in the wide range of ≈ 12-110 GHz. These mmW signals are transmitted over *RoF* links successfully through the co-simulation of the *Optisystem*^{TM} and *MATLAB*^{TM} to show the possibilities of the developed *EDFL* laser in *5G*-supported telecommunication-related applications. This work demonstrated as Section I illustrates the earlier reported approaches to generate mmW waves and the current developments. Section II describes an experimental set-up of the developed laser to generate phase-stable *RF* frequencies in the mid-boundary of the extra high frequency (*EHF*) range of the defined *5G* technology to realize a *RoF* transmission system. Section III demonstrates the transmission of *OFDM* signals over the *EDFL*-driven *RoF* system using *Optisystem*^{TM} and *MATLAB*^{TM} software. Section IV presents the conclusion.

II. EXPERIMENT SETUP FOR TUNABLE DUAL WAVELENGTH EDFL LASER

The ring-configuration of a simple, compact, and alignment-free *EDFL* laser set-up, with single-mode all-fiber integrated components, is shown in Fig. 1. The set-up employed a laser pump-source (980-nm) to pump a one-meter single-mode erbium-doped active fiber (*Liekki Er80-8/125*) using a wavelength-division multiplexer (980/1550 nm). Further, two polarization controllers (*PCs*) are incorporated in the laser-cavity with an optical isolator (*ISO*), forming a nonlinear polarization rotation configuration to control the birefringence for achieving an optimum amplification at the stable lasing-action [32]. Instead of using fused silica etalon as a tunable filter [33], a high-birefringence fiber (*HiBi*) has been used in this work as a birefringent filter and also to mitigate the inhomogeneous broadening of the Er-doped gain fiber. The HiBi fiber is also incorporated with two *PCs* to provide a wavelength-dependent polarization rotation with an optimum amplification performance by attaining a linearly polarized output. The *HiBi* fiber length is 10 m with a numerical aperture of 0.125, a core of 8.5 µm diameter, and cladding of 125 µm. It provides an extreme birefringence with polarization at the beat-length of ≈ 2.5 mm and attains a usable bandwidth of ≈ 12.5 THz. A polarization-independent ISO is also incorporated to achieve one-way circulation inside the laser-cavity. A 90:10 fiber coupler to redirect 90% of the signal power into the laser-cavity to attain optimum lasing action, and 10% out of the laser-cavity for spectral-and temporal- measurements, is used. The overall laser-cavity length is ≈ 18 m.

By measuring different laser dynamics without incorporating the HiBi fiber, the net laser-cavity birefringence is low [34-35]. In this work, an improved laser-cavity birefringence is attained, which tunes to ≈ 1.3 mm - 12 mm by precise tuning of the two *PCs*, due to attainment of the two orthogonal polarization refractive indices with minima (1.35×10^{-4}) and maxima (1.2×10^{-3}). Subsequently, the HiBi fiber provides a single-longitudinal mode operation with a tunable spacing and an improved FSR of the HiBi filter [32]. It produces a dual-wavelength spectrum with varying wavelength separation (0.1 nm-0.89 nm) corresponding to generate high carrier frequencies in mmW band (~12.3 GHz to ~110 GHz) in a tunable step of ~10 GHz shown in Fig. 1-2. The stability-spectra is recorded for a total time-span of 60 minutes at 0.02 nm spectrum resolution using an optical spectrum analyzer (*Yokogawa; AQ6370B; 600-1700nm*). The designed laser output shows a good power uniformity with power fluctuations of 0.32 dB and generates stable mmW waves of 56 GHz with wavelength fluctuations of 0.03 over an observation period of 60 minutes. Subsequently, a phase-stable RF spectrum is achievable as the minimal wavelength-fluctuations are recorded in this work without using any optical modulator, which causes instability in laser-based mmW wave generations due to fluctuations in *DC* biasing [36]. Moreover, the proposed *EDFL* laser is a simple and inexpensive structure contrast with without using any photonic-crystal fiber [37]. Fig. 2 shows the RF spectrum of the generated mmW waves at varying dual-wavelength spacing, Δλ of the proposed laser after photo-detection, and proper amplification using an *EDFA*.

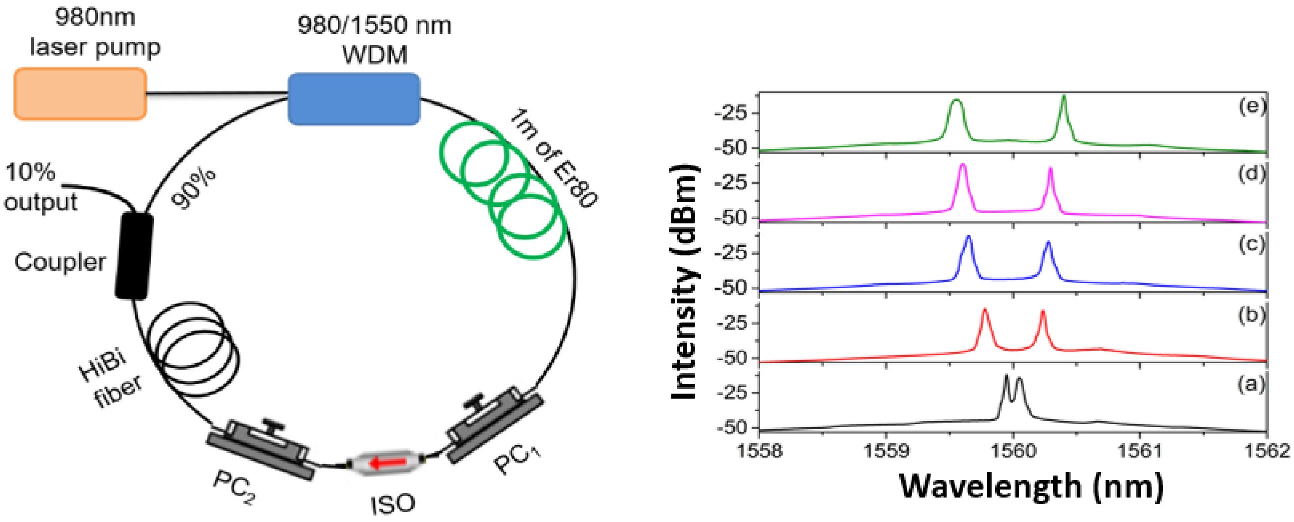

Fig. 1 Tunable dual-wavelength *EDFL* with dual-wavelength traces at different wavelength spacing [32]

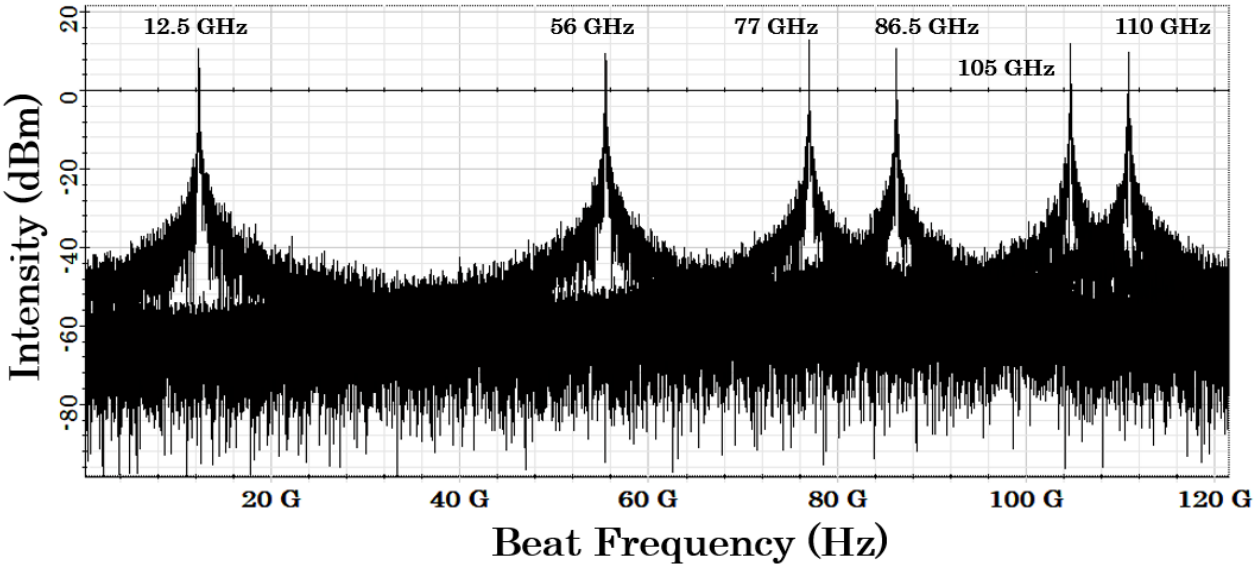

Fig. 2. RF spectrum of generated mmW waves ranging from 12.5 GHz to 110 GHz

III. SIMULATION SETUP FOR TRANSMISSION OF MMW WAVES OVER RADIO-OVER-FIBER LINK

In this section, an equivalent model of the experimentally designed *DWFL* laser in section II is developed using a well-known photonic module of *Optisystem^{TM}* to generate millimeter waves over a wide range of *12GHz-110GHz.* This *DWFL* laser model is further used to realize an *OFDM-RoF* transmission system at different RF frequencies. Besides it, the wireless channel incorporated with the antenna module is modeled in *MATLAB^{TM}* software. Fortunately, the photonic software contains a *MATLAB^{TM}* component tool that enables the system designers to integrate *MATLAB^{TM}* software-based modeled components within its environment (*Optisystem^{TM}*) using *MATLAB.dll* files. By co-simulating both software-based modeled sub-systems, the tunable *DWFL*-based mmW waves are generated and then transmitted over the *OFDM-RoF link*. The performance evaluation of the *DWFL derived OFDM-RoF* system is computed in terms of eye diagrams, bit-error-rate versus signal-to-noise ratio, and constellation diagram. Fig. 3 shows the simulation setup for transmitting the proposed laser-based generated *RF* signals over the *RoF* link. The *RoF* transmission system is designed in the mid-boundary of the extra high frequency (*EHF*) range of the defined 5G technology (*50 GHz-110 GHz*). For demonstrating the *RoF* system, the *OFDM* modulated data signals are generated employing an *M-ary QAM* digital modulation scheme to attain high spectral efficiency. In this work, *M = 16*, i.e. *16-QAM* modulation scheme is considered. These *OFDM* signals are then up-converted to the intermediate frequency (*IF*) using an *IQ* mixer and a local oscillator (*LO*) of 5 GHz shown in Fig. 3. The laser-cavity is adjusted carefully to generate dual-wavelength signals with a wavelength spacing of 0.46 nm (~ *56.7 GHz*) to transmit the *OFDM* signals over the *RoF* link. The dual-wavelength optical signals with a wavelength spacing of 0.46 nm (~ *56.7 GHz*) split into two different arms via *1:2*

DMUX. In the first arm, the *OFDM* data signals are modulated optically over the optical carrier frequency of 1559.40 nm using a single-arm external Mach Zehnder (*SAMZM*) modulator to generate dual sideband modulated signals (*ODSB*). The upper sideband is filtered out with an optical bandpass filter (*OBPF*) of center-wavelength of 1559.40 nm for obtaining the lower sideband of the *OFDM* signals (*LSB-OFDM*). This *LSB-OFDM* signal is multiplexed with the unmodulated carrier signal of arm two via *1:2 MUX* and then transmitted over the standard single-mode fiber (*SSMF*) of 20 Km [36]. For a multi-channel system or to accommodate more than one channel simultaneously over the attenuating fiber links for realizing the wavelength division multiplex (*WDM*) system, there is a probability of signal attenuation due to signal demultiplexing components. The multiplexed signals are amplified using low-noise and easily realizable erbium-doped fiber amplifiers (*EDFA*) before transmitting through the *RoF* link. The *EDFAs* are nearly unresponsive to the signal-polarization and offer flat-gain over a wider *RF* band. At radio access unit (*RAU*), the modulated *OFDM* signals and the unmodulated carrier signals are mixed in a *PIN* photo-detector (*0.8 A/W*) to generate the required mmW signals. These *OFDM* signals are then transmitted over a wireless link using a transmitting antenna with a gain of 25 dBi.

An Additive White Gaussian Noise (*AWGN*) wireless channel, with channel-parameters given in Table 1 is designed using *MATLAB*^{TM} and is integrated with the *Optisystem*^{TM} photonic-module to realize the *RoF* system. In the 55-60 GHz frequency band, the atmospheric factors like absorption by atmospheric gasses, water vapor-density, and other atmospheric constituents offer a significant signal-fading under dry and standard atmospheric situations [38-39]. It causes a weak signal reception at the radio unit (*RU*) and leads to a short transmission-range. Therefore, due to the high attenuation of signals in this frequency band with geometric losses, it is essential to restore the required signal power by applying a suitable amplification. Therefore, the received signals are amplified at the *RU* unit using a low-noise amplifier (*LNA*) of 17 dB in the demonstrated mmW band (*56 GHz- 110 GHz*) with noise figure of ≈ 5 dB [40-41] after propagating through the wireless link. These amplified signals are applied to a band pass filter (*BPF*) after *OFDM*-demodulation to retrieve the transmitted data signals.

TABLE 1. WIRELESS LINK PARAMETERS

Parameter	**Value**		
M	16		
No. of carriers	256		
No. of symbols	50		
OFDM bandwidth	2.5 GHz		
Wireless Channel	AWGN		
Wireless link	10 meter, and 50 meter		
Fiber link	20 Km		
Tx Antenna gain	25 dBi		
Rx Receiver gain	25 dBi		
	Frequency	**Attenuation @ Link range = 10 m**	**Attenuation @ Link range = 50 m**
Wireless Link Fading	56.7 GHz	87.5 dB	101.5 dB
	77.6 GHz	90.24 dB	104.2 dB
	86.2 GHz	91.15 dB	105.1 dB
	110 GHz	93.27 dB	107.2 dB

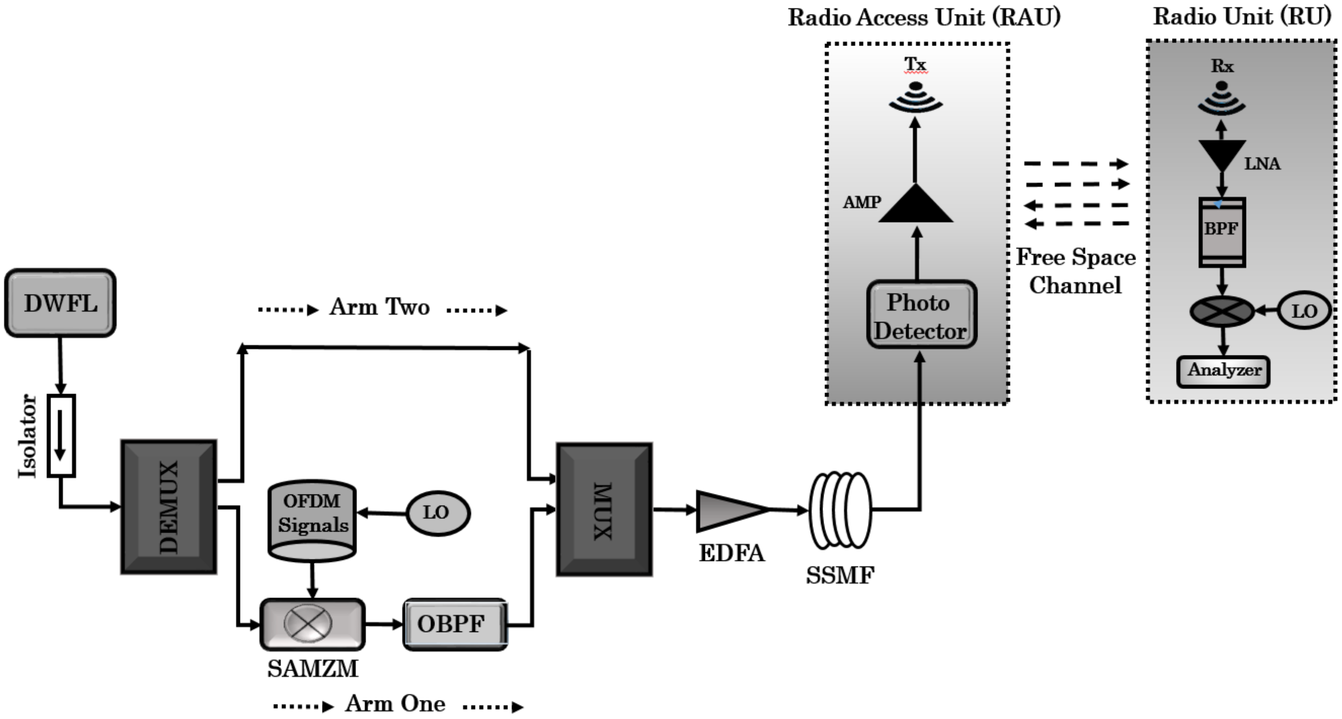

Fig. 3. Simulation setup of Tunable *DWFL*-driven *RoF* transmission system

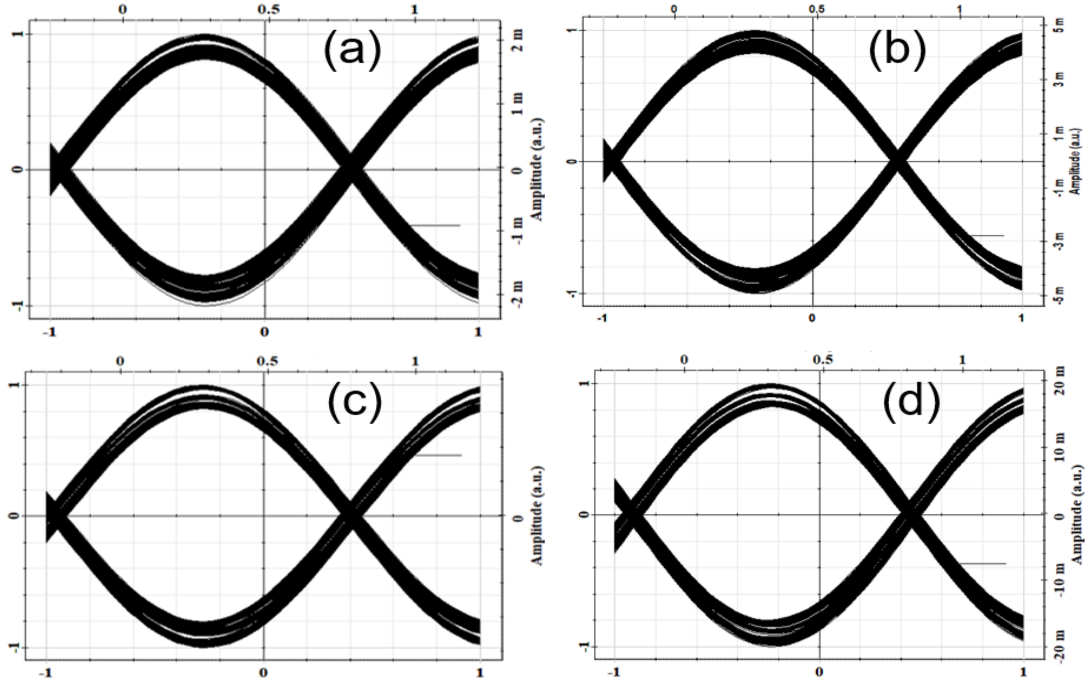

Fig. 4. Eye diagram estimation over fiber link of 20 Km at wavelength spacing of (a) 0.46 nm (b) 0.63 nm (c) 0.70 nm, and (d) 0.89 nm

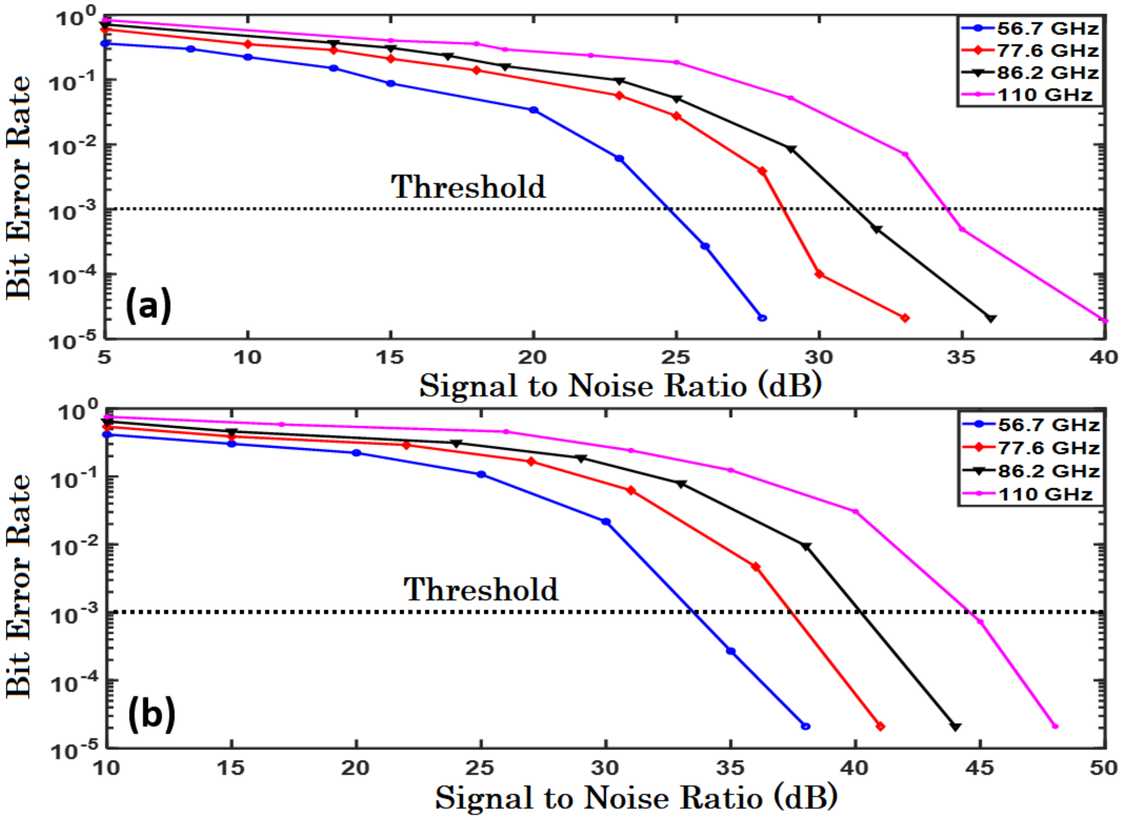

Fig.5. BER measurements versus SNR penalty at varied mmW signals over wireless link of (a) 10 meter, and (b) 50 meter

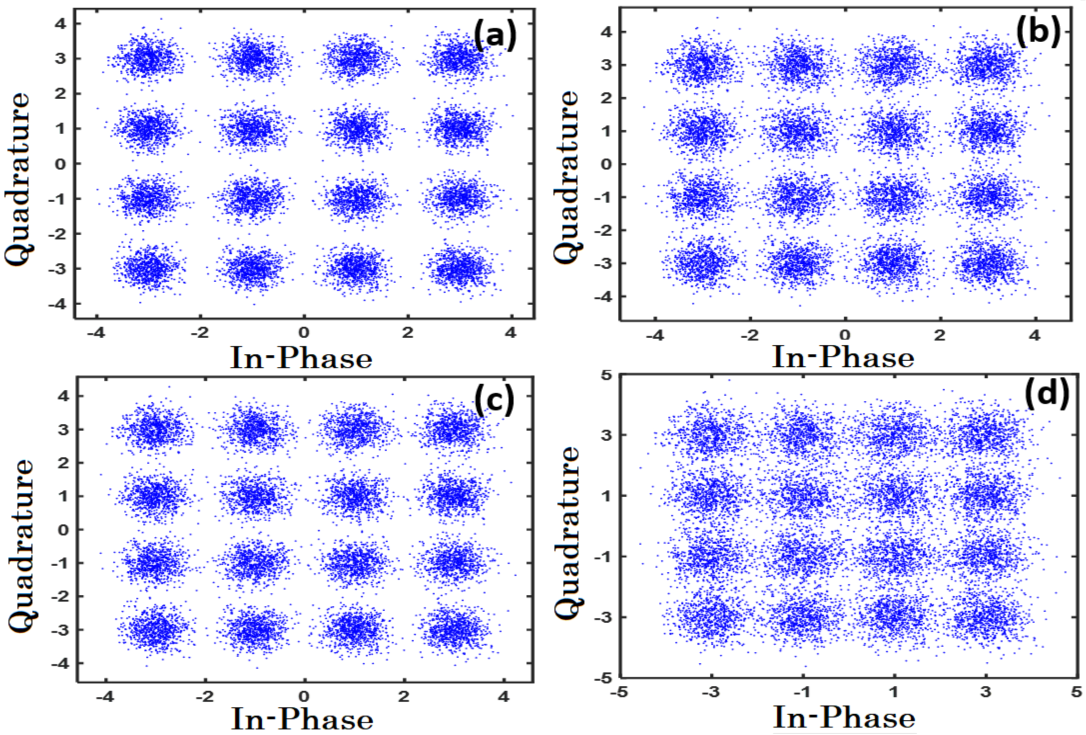

Fig.6. Constellation diagrams over wireless link of 10 meter at (a) 56.7 GHz (@ SNR = 25 dB, (b) 77.6 GHz (@ SNR = 29 dB, (c) 86.2 GHz (@ SNR = 31.5 dB, and (b) 110 GHz @ SNR = 35 dB

The results of the demonstrated dual-wavelength *EDFL* laser-driven *RoF* transmission system are depicted in Figs. 4-6, and shows the successful transmission of *OFDM* data-signals centered at the generated mmW frequencies (≈ 50 GHz -110 GHz) analogous to the dual-wavelength separation of the proposed dual-wavelength laser. Fig. 4 shows the eye diagram estimation of the transmitted signals over *SSMF* of 20 Km at varied wavelength spacing at the radio access unit after photo-detection. Furthermore, the *BER* estimation as a function of wireless link-length and *SNR* ratio is carried-out to achieve the threshold *BER* of 10^{-3}. The outcomes reveal that as the transmission occurs at a higher frequency of millimeter-wave band, the *SNR* penalty increases to obtain the threshold *BER* (10^{-3}). As per the atmospheric impact on the transmission of mmW signals beyond the mid-boundary of the *EHF* frequency band of the *5G* frequency spectrum [39-40], the link- length reduces along with the augmentation of power penalty to achieve the threshold *BER* as shown in Figs. 5-6. An *SNR* penalty of ≈ 25 dB and ≈ 34 dB is required to attain the BER of 10-3 at 55.6 GHz over a wireless link of 10 m and 50 m, respectively. For the successful transmission at 110 GHz, a power penalty of ≈ 35 dB and ≈ 45 dB is required over the demonstrated link lengths due to high-fading in this frequency-band. Thus, this work shows the feasibility of using the proposed laser for realizing the *RoF* transmission systems over a wide span of mmW band with a possibility of attaining an effective data rate of ≈ 100 Gbps over a wireless link up to ≈ 10 m using the existing state-of-the-art *75-110 GHz* antenna technology capable of providing a combined antenna gain of ≥ 48 dBi [42]. Moreover, the spatial diversity and beamforming techniques may play a significant role in achieving high transmission data rates in non-LOS environments at minimal power requirements.

IV. CONCLUSION

The demonstration of a tunable dual-wavelength *EDFL* laser to generate millimeter-wave signals over a wide range and their successful transmission over a *RoF* link is carried-out in this work. The proposed fiber-laser is designed in a ring NPR configuration using *HiBi* fiber and generates a broadened frequency range in the mmW band. In this work, the transmission of *EDFL* laser-generated mmW signals over the *RoF* link is reported using a fixed *OBPF* and *MUX/DMUX* corresponding to the wavelength spacing of 0.46 nm to generate mmW of ≈ 56 GHz. However, the *EDFL*-driven *OFDM-RoF* system is reconfigurable to the wavelength spacing of the laser's output using tunable optical bandpass filtering. Moreover, the system can be reconfigurable as per the tunablity of the developed laser-output using the software-defined network (*SDN*) technology and can be demonstrated as future work. Nevertheless, the authors believe that the proposed tunable laser has the probabilities in a wide range of *5G*-supported applications, including telecommunication, remote sensing, and tunable multiband photonics-based radar systems.

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