Improving radio-over-fiber systems using modulation instability phenomenon for satellite communication application

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***Abstract*—This paper proposes a low-cost, high-gain, low-noise microwave photonic structure using the modulation instability (MI) phenomenon for radio-over-fiber (RoF) systems. Conventionally, in modern satellite communication, the RoF structures always suffer from limitations of modulators that work at the high half-wave voltage (V_π) in high frequency and high noise, especially in case of weak signal reception.**

We demonstrate how the MI phenomenon improves the modulator's bias voltage. Therefore it is also possible to obtain acceptable gain and reduce optical shot noise without any complications by employing the proposed structure. Our suggested RoF structure can operate in the desired frequency band using a fiber switching control system.

Therefore, this system can reach a high gain by increasing the fiber length without needing external pumps. As a result, the SNR and the V_π improve noticeably.

I. Introduction

Modern radio frequency (RF) systems now operate at higher frequencies and more bands due to satellite communication's high capacity and broad instantaneous bandwidth needs. In order to satisfy the increasing throughput requirements while reducing frequency spectrum saturation and orbital resource scarcity difficulties, RF signal boosters are commonly used in communication satellites to convert communications between more frequency bands [1]–[4].

Microwave photonics (MWP) technologies may significantly impact optical inter-satellite communications in the future because of their high efficiency, wide bandwidth at low mass and small size [5]–[7]. Therefore, devices like the modulator have an essential role in achieving optimal results.

For the design of broadband traveling-wave modulators, increasing the V_π and frequency simultaneously is one of the fundamental challenges. In recent years, electronic devices have reduced their output voltage by raising the frequency, but in modulator devices like Mach-Zehnder modulator (MZM), this proportion is the opposite of what high frequency achieves at high V_π.

In these electro-optical (EO) modulators, the modulation voltage and arm length relationship are steady and constant ($V_\pi \times L = \alpha$, where α is constant). As a result, by lowering V_π, the arm length under the EO effect increases [8].

Despite there are other methods to improve the V_π, these methods like using new material [9] and using the ring resonator [10], have disadvantages such as high cost and complexity in structure.

A modern satellite communication system uses optical fibers to transmit the signal, which offers noticeable advantages, such as remarkably low loss and a reduction in the deviation frequency in the transmitted signal. Also, there is no such transmission delay due to the lack of signal encoding and decoding. All of the mentioned benefits are extremely necessary for satellite communication systems [11]–[13].

Improving the signal-to-noise ratio (SNR) is another necessity in satellite communication systems. This parameter defines how much of the transmitted signal is corrupted by noise. Also, the SNR is essential for sensors, because it determines the capabilities, efficiency, and cost. However, the noise affects the captured data extraction and scene interpretation. The dominant part of the noise is called shot noise. Shot noise is a signal-dependent phenomenon in many optical systems during photoelectric conversion [14]–[16].

In order to overcome the challenges mentioned above, MI is employed. MI is a nonlinear phenomenon caused by the interaction of diffraction, dispersion, and nonlinearity in the presence of an intense optical carrier wave (CW) that travels through a nonlinear medium. This paper will improve RoF links for satellite communication using the presented technique. In this method, by employing the MI phenomena in fiber optics, the half-wave-voltage ($V_{\pi,eff}$) has been reduced

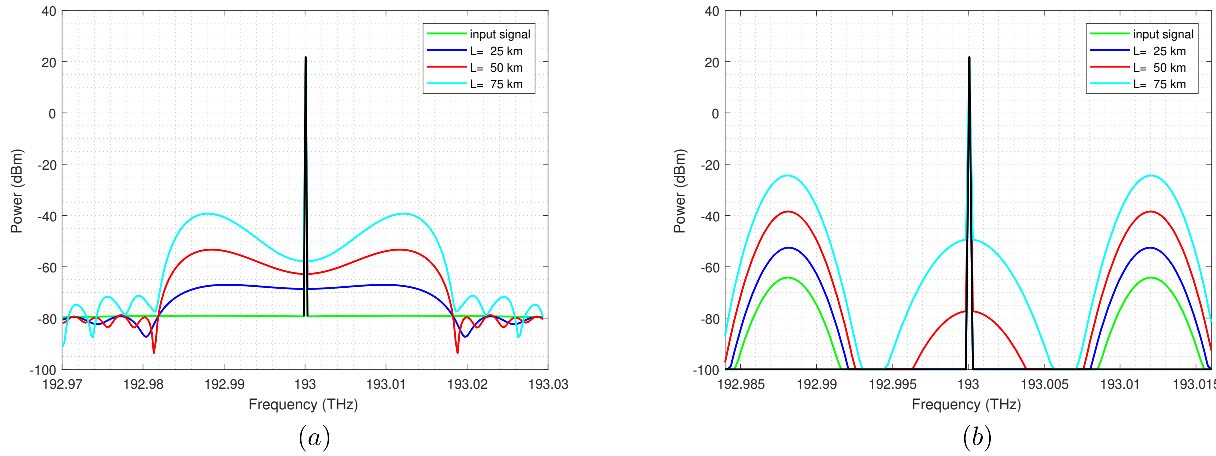

Fig. 1. Sideband amplification by different lengths of fiber with the a)-80 dBm power input and b)Gaussian pulse input with a central frequency of 12GHz.

for future high-frequency applications, and the system has also achieved significant gains in the carrier sideband for weak signals. This gain occurs spontaneously in the fiber and plays a considerable role which helps simplify the modulator's structure by discarding additional pumps and saving the input power consumption. On the other hand, improving $V_{\pi,eff}$ reduces the shot noise caused by the photodetector and raises the SNR, which improves satellite communication links.

The rest of the paper is organized as follows: Section II explains the MI in the fiber, the MI gain, and the effect of this phenomenon on the V_{π}. The proposed structure of the RoF system for satellite communication frequency bands is presented in section III. The noise reduction technique in the satellite system is discussed in section IV. Finally, the conclusions are summarized in Section V.

II. Modulation instability phenomena in fiber optic

Modulation instability is one of the most frequent phenomena in studying nonlinear waves. The unidirectional propagation of the envelope of nonlinear waves under the slowly varying envelope approximation is described in a wide range of domains, including optics, by the one-dimensional nonlinear Schrodinger equation.

In this situation, the optical pulse propagation using the nonlinear Schrodinger equation is as follows:

$$\imath \frac{\partial U}{\partial z} + \imath \frac{\alpha}{2} U - \frac{\beta_2}{2} \frac{\partial^2 U}{\partial T^2} + \gamma \left| U \right|^2 U = 0 \tag{1}$$

where U, α, β_2, and γ are the slowly varying envelope of the optical pulse, the loss factor of fiber, group velocity dispersion, and the non-linear parameter, respectively.

Eq. (1) can be easily solved by neglecting the time derivation to produce the steady-state continuous radiation solution. The continuous wave for the previous equation has a soliton form when the laser's response is lossless.

A. Modulation Instability's Gain

In the power of the laser, by considering the stability condition for the steady-state against small perturbation, the sideband gain is achieved by:

$$G_{MI}(\Omega) = |\beta_2 \Omega| \sqrt{\Omega_c^2 - \Omega^2} \tag{2}$$

Where the G_{MI} is the modulation instability gain, Ω is the frequency ,and $\Omega_c = \sqrt{\frac{4\gamma P_0}{|\beta_2|}}$ that P_0 is carrier power.

The nonlinear fiber with a specified design and under modulation instability amplifies a particular spectral range of the carrier sideband by nonlinear frequency variation on the laser wave under effect. This amplification can be applied and employed without a separate pump using only the anomalous fiber [17]. Moreover, in some long-distance wireless applications, the signal level the receiver detects is lower than the received signal level.

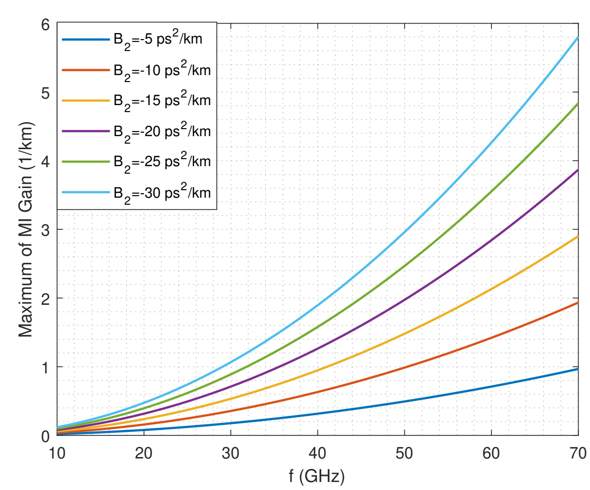

Fig. 2. The maximum gain of the nonlinear fiber under modulation instability with different group velocity dispersion (β_2) in the frequency range of 10 GHz $\leq f \leq$ 70 GHz.

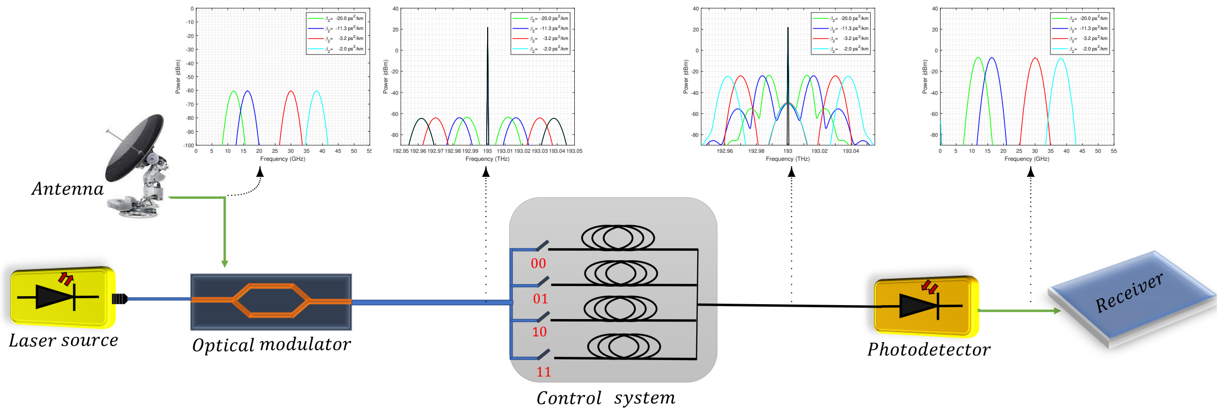

Fig. 3. Proposed structure of ROF system for different satellite communication frequency bands

Fig. 1 shows the sideband amplification for different lengths of fiber with the a) Gaussian pulse input with a central frequency of 12 GHz and b) a constant power of -80 dBm. The group velocity dispersion and nonlinear index of refraction of fiber are β_2=-20 ps^2/km, n_2= 10^{-20} $m^2.W^{-1}$, respectively. It is important to note that the carrier power is 300 mW, and the frequency is 193THz.

By raising the length of the fiber, the amount of gain at the sideband carrier increases too. The amount of gain per fiber length of 25 km, 50 km, and 75 km are 12.6 dB, 26.7 dB, and 38.1 dB, respectively.

The maximum gain (G_{max}=$\frac{\Omega_c^2|B_2|}{2}$) happens at frequency Ω_{max}=$\pm\frac{\Omega_c}{\sqrt{2}}$.

Fig. 2 illustrates the maximum MI gain vs. frequency at different group velocity dispersion. In this case, in a fixed gain, with β_2 change, this application can be applied to other frequency bands.

The signal quality and power of the electromagnetic (EM) signal transfer reduce so much because of the atmospheric attenuation. In this situation, obtaining a high gain is vital for communication networks by reducing the value of path loss.

B. V_π Challenge in Mach-Zehnder Modulator

Increasing the V_π with regards to raising the frequency is one of the critical challenges in designing broadband traveling-wave modulators like MZ that have approved performance. However, this ratio is inverse in electrical devices like CMOS [18]. Using the MZM in the proposed structure makes it possible to modulate the Gaussian pulse on the carrier. One of the benefits of this structure is by helping MI gain in the sideband of the carrier, V_π of the MZM improved as a following:

$$V_{\pi,eff}(w_{RF}) = V_\pi(w_{RF})\frac{L_{Dep}^{1/2}}{G_{MI}^{1/2}(w_{RF})} \tag{3}$$

In this equation, $L_{Dep}^{1/2}$ ¡1 is the consumption factor for the power carrier. The effective half wave voltage $V_{\pi,eff}$ is decreased by utilizing the G_{MI} in the sideband, which helps to overcoming the V_π challenge.

Although in transmitting and receiving communication applications, the modulator's performance is enhanced by raising the gain, which lowers the $V_{\pi,eff}$ and improves the detection of the received signal. It is crucial to remember that a fiber operating under MI will inherently amplify pulses without the assistance of an additional pump or amplifier. Therefore, achieving the improvement at V_π with MI is possible.

III. ROF CONTROL SYSTEM STRUCTURE

RoF technology is a useful technique that enhances the satellite communication range and simultaneously reduces signal loss. It consists of the MZM, where the light is modulated by the RF signal, and a photodetector, where the radio signal is extracted from the optical signal. These two devices are connected by an optical fiber [19].

The proposed RoF system is shown schematically in Fig. 3.

The desired signals are modulated by the MZM, and due to the phenomenon of MI, it is placed in the sideband of the carrier and amplified. This amplification is related to the frequency, carrier power, and fiber parameters. Then, the control system selects the fiber according to the desired frequency band to create the best satellite communication link. The output of this system is shown simultaneously for four inputs in four different frequency bands, each of which passes through its fiber.

Each fiber is selected by changing the β_2 based on the corresponding frequency. According to the length of 75 km of the fibers under modulation instability, the 38.1 dB gain can be achieved (raised from -64 dBm to -25.9 dBm).

Finally, based on the required maximum gain, and by keeping away the signal from distortion, the V_π is enhanced. Table 1 shows the gain and improvement of V_π upon fiber features and the frequency, where the acquired gain is by almost 38.1 dB, and we achieve over 70 times reduction in V_π. It is necessary to indicate that our proposed system, by avoiding using another structure like an external pump for amplifying the signal level, is more economical and also decreases the noise level.

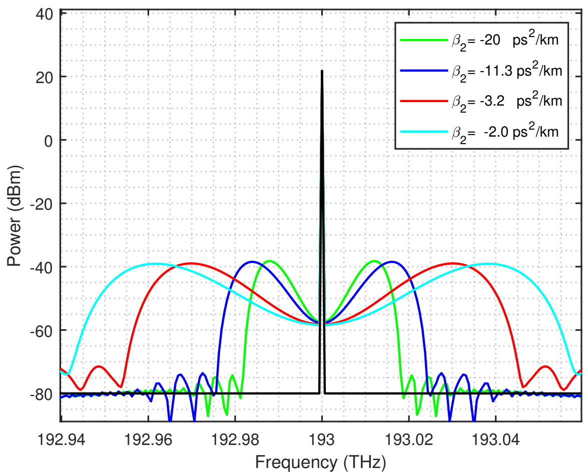

Fig. 4. MI gain by different group velocity dispersion (β_2) of the fiber with 75 km length and by -80 dBm input power

Fig. 4 shows the fiber output per input with a constant -80 dBm power in a wider spectrum. As we can see, the amplified frequency band changes with the β_2 change of the fiber.

TABLE I
PROPOSED ROF SYSTEM RESULT

$f(GHz)$	$\beta_2(ps^2/km)$	$L(km)$	$Gain(dB)$	$V_{\pi,eff}$
10-14	-20	1	0.5	$\propto 0.937V_\pi$
10-14	-20	25	12.6	$\propto 0.230V_\pi$
10-14	-20	50	26.7	$\propto 0.046V_\pi$
10-14	-20	75	38.1	$\propto 0.012V_\pi$
14-18	-11.3	75	38.1	$\propto 0.012V_\pi$
28-32	-3.2	75	38.1	$\propto 0.012V_\pi$
36-40	-2.0	75	38.1	$\propto 0.012V_\pi$

IV. NOISE REDUCTION IN ROF SYSTEM

The random variation in the appearance of electrons and holes at the device's output side causes shot noise in a communication channel. Because of faults in the system's device, these unpredictable motions have been seen. It also happens with PN junction diodes, as though the action of an external potential is what causes the movement of carriers within the diode. Thus, the system's nonlinearity or discontinuity produces shot noise.

Furthermore, the SNR in photonic microwave structures is proportional to the inverse square of the $V_{\pi,eff}$, which improves the SNR due to its reduction and channel capacity [20].

$$SNR = \frac{PP_{RF,in}Z_mR_d}{4q\Delta f}\frac{\pi^2}{V^2_{\pi,eff}} \tag{4}$$

Where Z_m is the electrical impedance of the modulator, R_d is the photodetector responsivity expressed as the ratio of the photo-generated electrical current divided by the incident optical power, Δf is the RF bandwidth, and q is the elementary charge. Therefore, by increasing the gain and improving the voltage of the modulator, the effect of noise decreases.

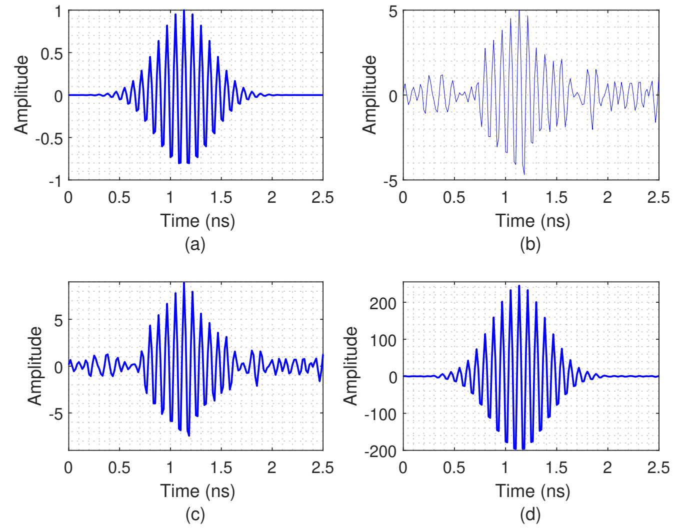

Fig. 5. Shot noise effect on the a) input RF signal with proposed structure by the different fiber length and with the amount of SNR b) 2.23 dB for L= 5 Km, c) 8 dB for L= 20 Km, and d) 38.1 dB for L= 75 Km.

Fig. 5 shows the reduction of the shot noise effect by increasing the fiber length of L = 5 km, 20 km, and 75 km.

In this case, the ROF system response with Gaussian pulse is displayed, and the photodetector contains shot noise with the power of -36 dBm. By using this technique and increasing the fiber length, the MI gain is increased, and the effect of noise is reduced significantly.

Fig. 6 illustrates the output signal power and SNR vs. fiber length for different carrier power. In fact, by increasing the laser power or fiber length, the gain or SNR can be improved. It is essential to note that we can achieve the same gain or SNR with a longer fiber length to recompense the effect of the lower power of the laser.

V. CONCLUSION

We demonstrated by using optical fibers under the MI phenomenon in the proposed RoF system, it is possible to improve significantly the MZM bias voltage, system gain, and optical shot noise. This technique can be implemented

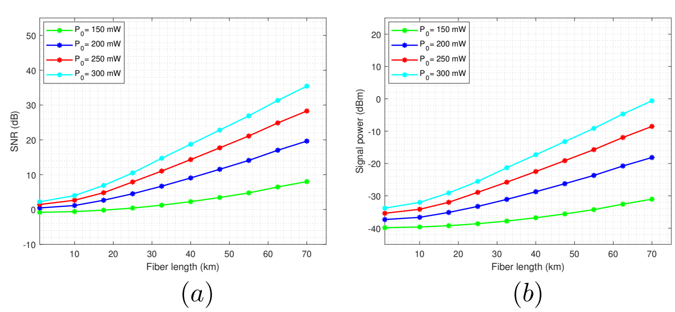

Fig. 6. Output signal power and SNR vs. fiber length for different power of laser

for different frequency bands using a control system based on the variation of the β_2. In the proposed RoF system, RF signal with the central frequencies of 12, 16, 30, and 38 passes through the fiber with lengths of 1 km to 75 km.

Unlike conventional systems, the system's gain increase as the fiber's length increases. In this case, when using a 75 km fiber, the gain reaches 38.1 dB and achieves over 70 times reduction in V_π.

Therefore it is a good candidate structure for satellite communication systems.

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