Testing RFoF Link for Transmitting HF-OTHR Signal Between Transmitter and Receiver shelters

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Abstract **—HF-OTHR site contains two equipment shelters, up to 1 km away from each other, that need to be connected for transmitting FMCW signal. This connection, if realized using coaxial cable, has shown itself to be vulnerable to external electromagnetic discharges, which can damage the sensitive radar equipment. This paper explores and tests the possibility of using Radio Frequency over Fiber (RFoF) link as an alternative to coaxial cable for transmission of signal, in order to ensure the immunity from external sources of electromagnetic interference (EMI).**

Keywords **— Electromagnetic Interference, High Frequency Over the Horizon Radar, Radio Frequency over Fiber.**

I. Introduction

HIGH-Frequency Over-the-Horizon Radar (HF-OTHR) is an effective solution to maritime monitoring at distances up to 200 nautical miles (370 km) from the shore [1-4]. Equipment of the HF-OTHR system is stored inside two shelters, located up to 1 km apart [3]. Radar signal is generated inside the shelter located near the receiving array (Rx shelter) of the radar and needs to be transmitted to the shelter near the transmitting array (Tx shelter), where it is amplified and fed into antennas which radiate it towards the sea. In existing OTHR installation in Gulf of Guinea, this connection is realized using a 50 Ω coaxial cable, called Rx-Tx cable. This cable is grounded at multiple places, according to standard [5].

During regular operation of the HF-OTHR systems installed in Gulf of Guinea, it was noticed that system components connected to both sides of Rx-Tx coaxial cable occasionally suffered damage to their terminal circuits. Installation of protective circuits (attenuators, Surge protectors, Over-voltage protectors) protected the system components, but the protective circuits themselves continued to be damaged from time to time, requiring occasional visits to remote HF-OTHR sites which can be expensive at best, and dangerous at worst of times. Due to location of malfunctions, it was concluded that the surge of electricity that damaged the system was induced inside Rx-Tx cable.

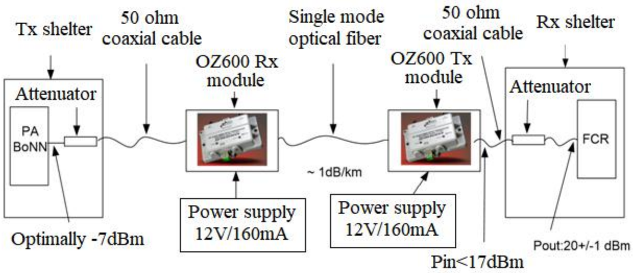

Fig. 1. Block schematic of shelters of HF-OTHR with a proposed realization of RFoF link.

As a possible solution to this problem a Radio-Frequency-over-Fiber (RFoF) link is proposed as an alternative to coaxial cable for connecting Rx and Tx equipment shelters (Fig. 1.). This link uses electro-optical converters to convert radio frequency signal into optical signal. This optical signal can then be transferred over optical fiber to its destination where it is converted back into radio frequency electrical signal. This would remove the need for coaxial connection between two shelters and galvanically isolate equipment shelters. As optical fibers are extremely resistant to electromagnetic interference (EMI) this would also solve the problem of extrenal discharges damaging HF-OTHR equipment [6].

This approach is elaborated in section II. Laboratory measurements of RFoF link are presented in section III, while section IV contains the measurements done inside the equipment shelters. Section V contains the discussion of results of measurements and conclusion.

II. Radio-Frequency-over-Fiber link

To combat these surges of electricity which can damage the equipment, the solution described in this paper was proposed. Instead of transmitting the signal from Rx to Tx shelters via the coaxial cable, the Radio Frequency over Fiber link would be used. RFoF link was realized using a pair of OZ600 modules (Fig. 2.), manufactured by Optical Zonu [7]. RFoF link consists of two separate modules, connected with a single-mode optical fiber. To authors' knowledge, RFoF link in question was not tested for the

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extremelly low-noise application such as HF-OTHR.

Parameter	Value
Gain	3 dB
Max. Input power	17 dBm
Bandwidth	10 kHz – 3.3 GHz
Phase characteristic	Linear, group delay variations listed for frequencies higher than 30 MHz only.
Input/Output Impedance	50 Ω
Noise Figure	40 dB

Table 1. Parameters of interest for OZ600 modules taken from datasheet.

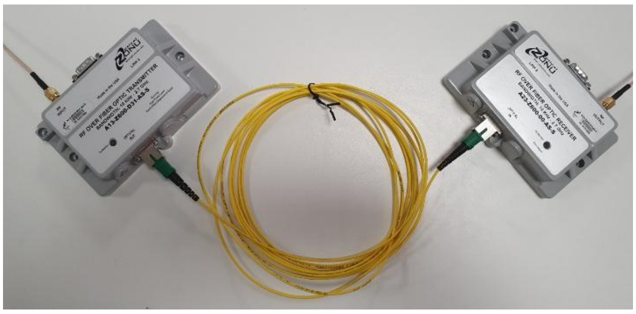

Fig. 2. OZ600 modules connected with an optical fiber. Coaxial cables used for transferring radio signal can also be seen on the sides.

To be able to apply it as a connection between Rx and Tx shelters the following requirements had to be met:

- Gain/losses: Output signal must not drop below -7 dBm;
- Phase characteristic must be linear;
- Noise figure: it must not introduce any excess noise compared to coaxial cable;
- Phase noise: it must not raise phase noise of the signal compared to coaxial cable.

Power budget for Rx-Tx link was calculated and given in Fig. 1. Additionally, Noise Figure is given in [8] to be 40 dB. Maximal output power of radar signal generator is 20 dBm. This power is attenuated by 10 dB before RFoF in order to protect the output of radar in case of malfunction of RFoF. This gives the theoretical limit of the signal to noise ratio (SNR) of around 90 dB for a signal with 100 kHz bandwidth [9]. This SNR was deemed high enough for usage in HF-OTHR. It is worth noting that this SNR is calculated for a situation when only thermal noise is present at the input of RFoF link. In real applications other sources of noise can also be present: in this particular implementation most dominant is quantization and phase noise of Digital-to-Analog converters in frequency synthesizer. However, as these sources of noise exist regardless what is used to connect Rx and Tx shelters, this analysis implies that this realization of RFoF itself will not introduce significant noise into the system, which could degrade performance. After demodulation, FFT is performed on the signal which produces a system gain proportional to the duration of sample, which improves SNR in the final result.

III. RFoF Laboratory Testing

RFoF link had to be tested locally, in order to assure its proper operation before being integrated into existing systems, because any repair work after installation becomes progressively more difficult due to the remote location of HF-OTHR sites. A series of tests was performed on the RFoF link to quantify the parameters listed in the previous chapter. Firstly, the gain and the linearity of the phase were tested using the Vector Network Analyzer (VNA) Bode 100. 2-port calibration was performed before the measurement at the ends of the coaxial connectors. Frequency band at which the module was tested was between 4.4 MHz and 5 MHz. The reason for that was because the receiver modules used for later tests were optimized to operate in that band. Full measurement setup is given in Fig. 3. The results showed a gain of around 6 dB in the band of interest (Fig. 4.), which is slightly higher than listed in the datasheet. Additionally, phase characteristic is shown to be linear.

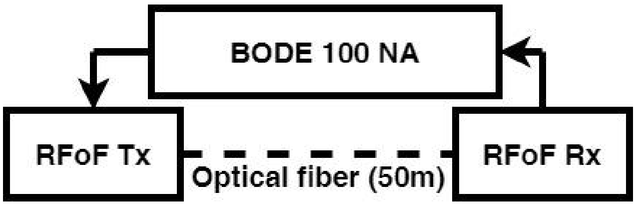

Fig. 3. Measurement setup for quantifying gain and linearity of phase characteristic. Full lines denote coaxial connections, while dotted line represents fiber connector.

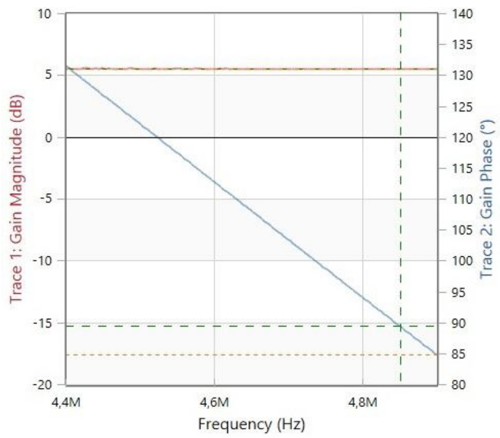

Fig. 4. Gain (red trace) and phase characteristic (blue trace) of RFoF link when measured according to Fig. 2.

$$\tau_g = -\partial\varphi / \partial\omega; \tag{1}$$

Due to the way RFoF conversion is done, every 1 dB of losses in optical power corresponds to 2 dB loss in RF power [8]. However, due to the low losses of modern optical fibers, it can be concluded that for distances of up to 1 km, which are of interest, RFoF link would still have a positive net gain [10].

Due to linearity of phase characteristic, group delay can be easily calculated by Eq. (1). The measurement can be performed on site to calculate the exact delay that RFoF connection will introduce in signal path. Then, HF-OTHR can be calibrated for this length, so as not to offset its range estimation due to delay. The same calibration is performed when Rx-Tx cable is coaxial, so no additional changes to the system and signal processing needs to be implemented. It is worth noting that optical fibers found commercially have a very low delay per unit length, so total delay of the signal is expected to be comparable to the delay in coaxial cable.

IV. Testing in HF-OTHR Shelters

Any excess noise inserted on the line between Rx and Tx shelters will be amplified by PA and radiated, which can severely impair the ability of the system to discern distant targets. For that reason the amount of noise inserted with RFoF link between FCR and PA needs to be compared to the amount of noise existing when PA is connected to FCR with a coaxial cable. To measure the level of noise inserted by RFoF link, external sources of noise had to be excluded, because they will be picked up by receiving antennas regardless of whether coaxial cable of RFoF is used. Additionally, receiver of HF-OTHR has a much finer frequency resolution than any Spectrum Analyzers (SA) the authors had access to. This allows the mean noise level to be reduced sufficiently so that the phase noise levels can be gauged with great precision. It is for this reason that noise measurements were performed in the shelters of the HF-OTHR, using its transmitter, Power amplifier and receiver modules. The measurement setup for comparing the amount of noise with and without RFoF link is shown in Fig. 5.

Connection between Rx and Tx block on Fig. 5. represents the location where the coaxial cable will be replaced with RFoF link. RER1 and RER2 are Receiver Racks, each of them containing eight receiver modules. Attenuators on both ends of connection between Rx and Tx serve a dual purpose of attenuating a signal to an optimal level for PA and RFoF link, and protecting equipment (FCR and PA) by providing a good impedance match for both of them in case a connection between them is removed for any reason. To test both coaxial cable connection and RFoF link, a set of measurements with a sinusoidal excitation was performed.

The length of both the coaxial cable and optical fiber is small enough for attenuation from losses in them to be ignored. Instead of regular chirp signal, the FCR was set to emit a sinusoidal signal at the frequency 4.6 MHz, for the predefined duration of around 67 seconds, which is equal to 256 chirp intervals. That signal is transmitted towards the PA, amplified, then attenuated to a sufficient level and divided across the sixteen receiver channels of HF-OTHR.

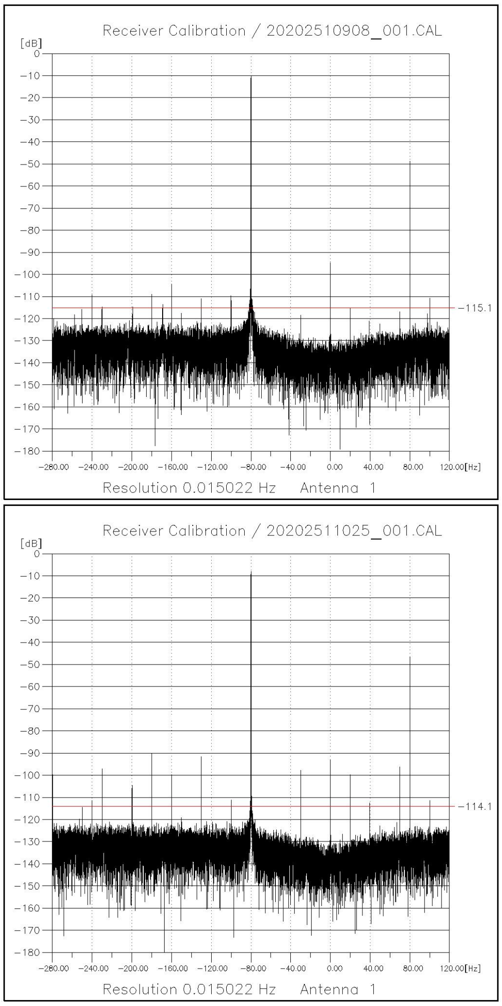

Fig. 6. Measurement of noise when Tx and Rx are connected with coaxial cable (up) and RFoF link (down).

There, a signal is demodulated by a sinusoidal signal at a frequency that is 80 Hz away from the received signal. After IQ demodulation, this leads to a demodulated signal in the form of complex sine signal at the frequency of -80 Hz. Demodulated signal is sampled with an Analog-to-Digital converter at the frequency of sampling of $V_{sample} \approx$ 6kSps. A Fast Fourier transform (FFT) was performed on the resulting samples and a part of spectrum

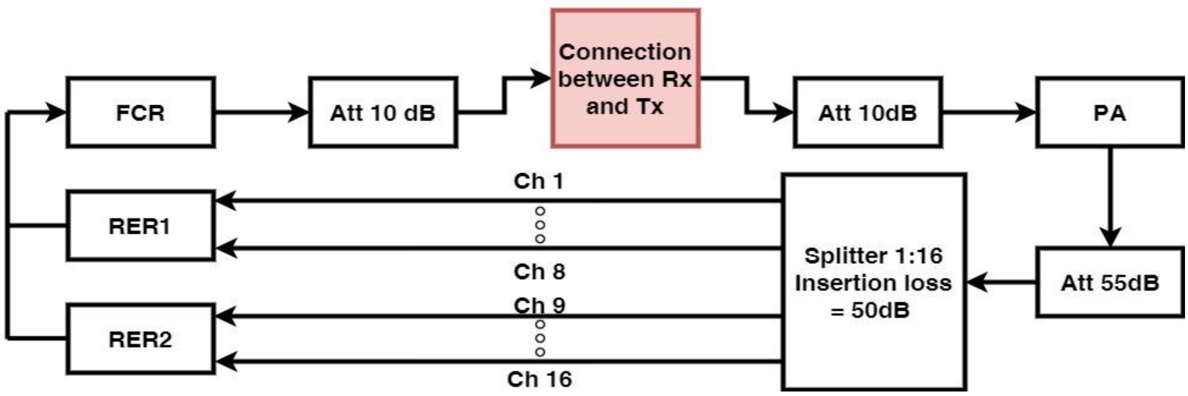

Fig. 5. Measurement setup for measuring noise and phase noise insertion of RFoF link.

between -280 Hz and 120 Hz was compared for coaxial connection and RFoF connection. Frequency resolution of this FFT is Δf = 0.015022 Hz, which is much finer than the resolution of most commercially available spectrum analyzers. When it comes to noise levels and phase noise levels, HF-OTHR requirements are extremely strict:

- Noise level after demodulation has to be at least 120 dB below the nominal level for a given frequency resolution;
- Phase noise, after demodulation at ±2 Hz from a demodulated sinusoidal signal, has to be at least 100 dB lower than the signal.

Fig. 6. shows results of this measurement, for receiver channel 1, when FCR and PA are connected using a coaxial cable as well as the results of the same measurement when a connection is realized via RFoF link. Both of these figures show a spectrum in logarithmic scale, relative to a nominal receiver signal level of -45 dBm.

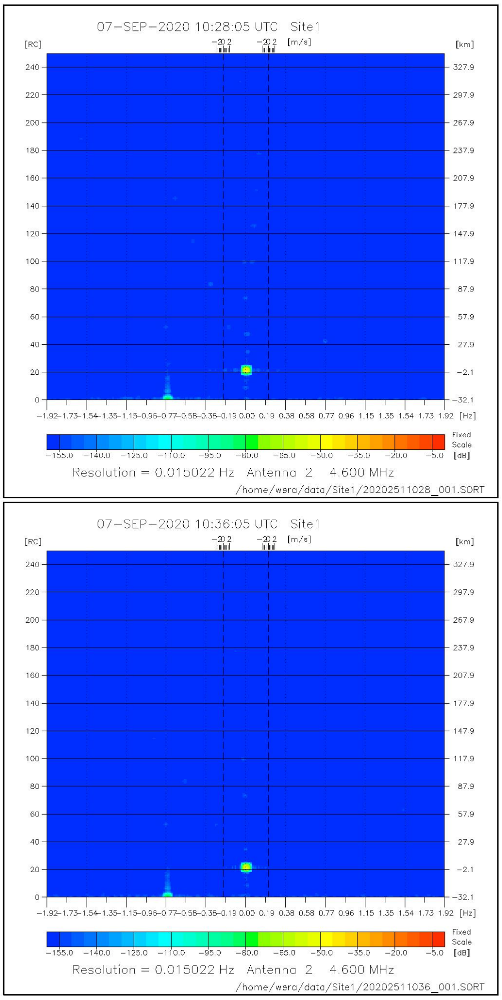

Fig. 7. Range-Doppler map of a simulated radar target when Rx-Tx connection is realized via coaxial cable (up) and RFoF link (down).

Measurements with chirp signals were also performed. Measurement setup was the same, only instead of emitting a continuous sinusoidal signal, FCR was set up so that it emits chirps of approximate duration of 260 ms. The time of measurement stays the same, at around 67 seconds. Emitted and reference signals were again separated in frequency by 80 Hz, which leads to a simulation of radar target at the 20th resolution cell. On this set of chirps both the Range and Doppler processing algorithms were performed [1][11]. Results of these measurements are shown on Fig. 7.

V. CONCLUSION

RFoF link was tested as a connection between Tx and Rx shelters of HF-OTHR system. All of the requirements given in chapter III are fulfilled. Gain of tested RFoF link is around 6 dB, constant over bandwidth of interest. It can be expected that this gain will drop with increase of length of optical fiber, but it is not expected that this lowering of gain will influence the operation for ranges of interest. Phase characteristic was linear, which translates to a constant group delay over entire bandwidth. These results are satisfactory.

There is no noticeable noise or phase noise increase when RFoF link is used compared to the case where a coaxial cable is used. Test with a simulated radar target showed that RFoF link transferred the chirp signal as well as the sinusoidal signal, with simulated target as clearly defined as with coaxial cable.

Results of these tests imply that RFoF connection performs at least as well as coaxial cable when it comes to connecting Rx and Tx shelters of HF-OTHR: it does not degrade radar processing. These results are promising, and are an incentive for the RFoF links to be installed in already existing HF-OTHR systems. Further testing will be done once RFoF modules are installed in operating HF-OTHR systems. The true test of RFoF link, or rather its ability to protect the system from external EMI, can only be performed on the field, during regular radar operation.

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