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*Article*

# Experimental Demonstration of Channel Routing of Microwave Signals Sharing an Optical Link by Using a Tunable Optical Band-Pass Filter

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**Abstract.** The imperative need to share an optical link to optimize its use among multiple users for data distribution continues to be a topic of technological challenge. In this regard, it is well known that one of the most common techniques is the WDM technology. However, this paper describes a technical alternative that enables channel routing for data sharing over an optical link between two users using a tunable Optical Band-Pass (OBP) filter. This proposal is experimentally validated. To demonstrate the viability of this approach, microwave signals are used as data. The selected microwave signal is wirelessly transmitted at the end of the optical link. The signal-to-noise ratio (SNR) parameter measure is adopted to evaluate the quality of each microwave signal, achieving an average SNR of 37.01dB. This proposal is validated for microwave signals within the S-band (2 to 4 GHz), however, this frequency interval can be expanded. Potentially, this approach allows the sharing of optical fiber among multiple users to deliver services via wireless links in indoor environments.

**Keywords:** Tunable optical band-pass filter, optical fibers, microwave signals, wireless links.

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## 1. Introduction

Currently, optical communications systems are utilized to deliver data at high speeds and frequencies. In this regard, optical links supply a high bandwidth, and optical fibers are the only medium capable of transporting these tremendous amounts of data through long distances [1]. Due to its great performance, optical fibers are not only used in optical communications. Its field of applications is extensive, for example, in [2], optical fiber is used as a biosensor. To maximize the utilization of an optical link between multiple users [3], several approaches are used, such as Wavelength Division Multiplexing (WDM) [4, 5, 6, 7, 8], Optical Time Division Multiplexing (OTDM) [9, 10, 11], Polarization Multiplexing (POL-MUX) technique [12, 13, 14, 15], and Spatial Division Multiplexing (SDM) [16, 17, 18, 19, 20], among others. On the other hand, wireless technology is more flexible and adaptable than wired networks. This technology provides high mobility for users, which is one of the main reasons for its preference over wired networks [21]. Thus, the coalition of optical and wireless techniques allows to delivery services such as the Internet, TV on-demand, and telephony in a hybrid way [22]. In this regard, numerous works have been published in the last few years, for instance, in [23] an experimental investigation of mobile networks using optical fibers is carried out. In [24], the experimental results of an optical fiber and wireless link deployment within a 5G Radio Access Network (RAN) are described. In [25], a system architecture and hardware development status for a High-Speed Train Radio Communication system, using an optical-wireless transmission in the W-band is presented. In [26], a bidirectional hybrid OFDM-based Wireless-over-fiber architecture has been investigated and demonstrated for uplink and downlink transmissions. In [27], the authors present a study for the design and simulation of a Radio over Fiber (RoF) system operating at 64 GHz. In [28], a hybrid digital and analog system is proposed. Finally, in [29] an indoor Digital Optical-Radio transmission system for both Cellular and IoT services is described.

In light of the previously described context, knowing that an Optical Band-Pass (OBP) filter allows specific wavelengths of light to pass through while blocking others, these devices find a wide variety of applications, including spectroscopy, fluorescence microscopy, and telecommunications. Thus, the motivation of this work is to propose the use of a tunable OBP filter as a key device for channel routing the data that is shared in a single optical link. This proposal is validated for the case of two users sharing an optical link and using microwave signals (MW) as data [30]. Thus, thanks to the use of the tunable OBP filter it is possible to select one or another MW signal. Another challenge, but not least, is that the selected MW signal is wirelessly transmitted in an indoor environment. Therefore, the main contribution of this proposal is the practical demonstration of the use of an OBP filter for the channel routing of microwave signals sharing an optical link avoiding the use of multiplexers and demultiplexer devices.

The remaining parts of this paper are structured as follows: The experimental setup and its operating principle are described in Section 2. Section 3 presents a discussion of the results. Finally, the manuscript ends with the conclusions presented in Section 4.

## 2. Experimental Setup

The experimental setup is represented in Fig. 1. Its operation is described below; however, before discussing the operation of the setup . Firstly, the main characteristics of the optical sources, OBP filter, and antennas are presented.

### 2.1. Optical Sources

The Distributed Feedback lasers DFB_1 (LP1550-SAD2-230109-19, $\lambda_1 = 1548.26$ nm) and DFB_2 (LP1550-SAD2-181115-11, $\lambda_2 = 1550.22$ nm) are characterized. These DFBs are driven by controllers at a polarization current of 11.1 and 11.8 mA, respectively, ensuring a stable optical power of 1 mW for each one. Their respective current-power and optical spectra curves registered by an Optical Spectrum Analyzer (Anritsu MS9740A) are shown in Fig. 2 and Fig. 3, respectively.

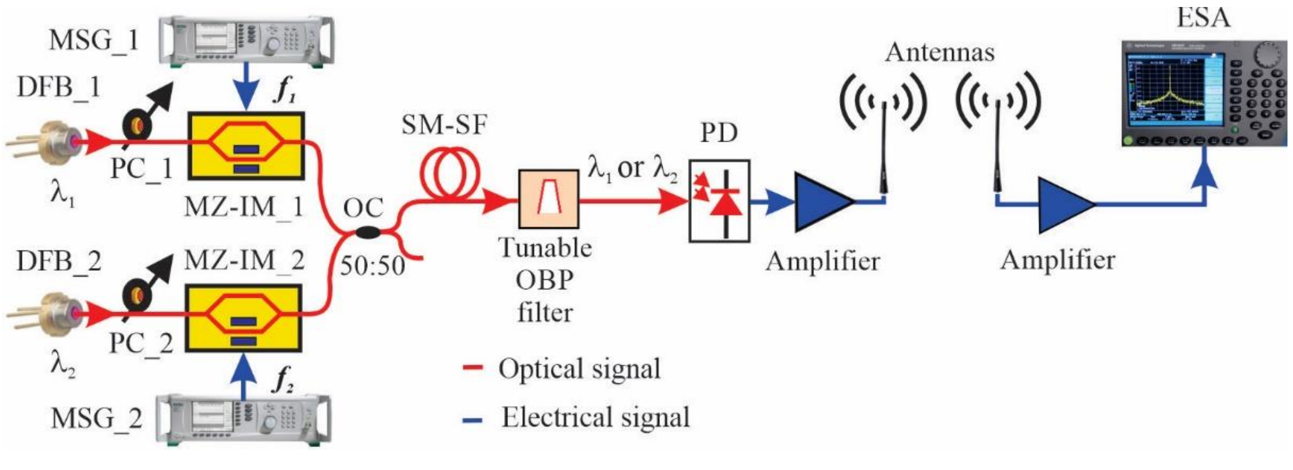

Fig. 1. Experimental arrangement to recover two microwave signals sharing an optical link using a tunable OBP filter.

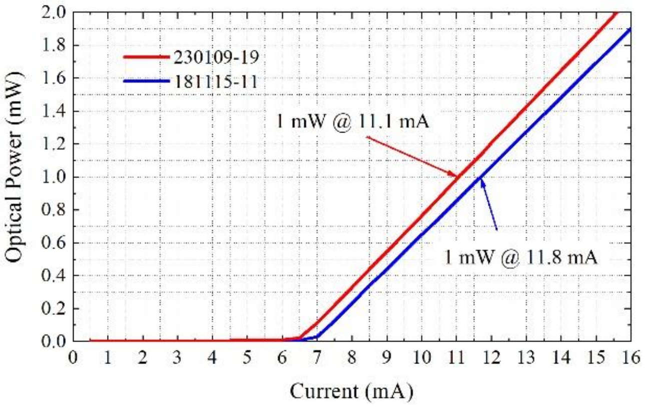

Fig. 2. Current-power curve for the DFB_1 and DFB_2.

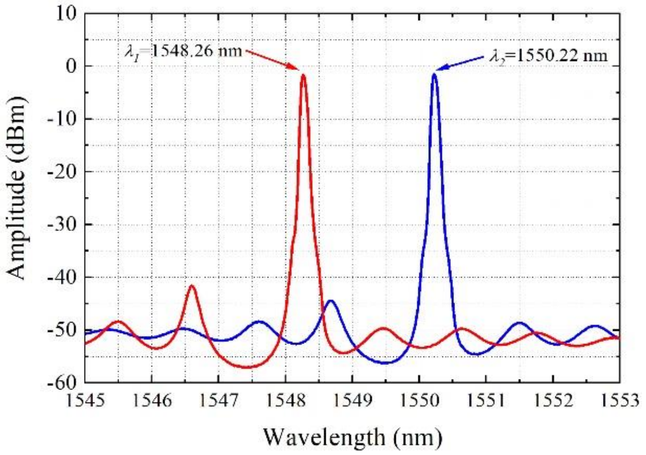

Fig. 3. Optical spectrum for the DFB_1 and the DFB_2.

## 2.2. Optical Bandpass Filter

The key device of the experimental setup shown in Fig. 1 is the tunable OBP filter (TF-1550-0.8-9/9LT-FC/APC-1) [31]. An OBP filter is a device that allows a specified range of wavelengths to pass through with high transmittance while blocking all others. According to the manufacturer's datasheet for the Optical Bandpass Filter [31], the tuning range of this device is 1535 to 1565 nm (C-band), therefore, 1565 - 1535 = 30 nm. This means that at least 30 different wavelengths around 1550 nm can pass through this optical filter.

## 2.3. Antennas

Two Indoor Directional Patch antennas (WiMo HIF-2400 WaveLAN Antenna, with a central frequency of 2.4 GHz, a bandwidth of 100 MHz, and a Gain of 8.5dBi) [32] are used for the wireless transmission of the recovered microwave signals. Once the optical and electrical characteristics of the aforementioned devices have been established, the next step is to describe in detail the experiment.

## 2.4. Description of the Experiment

As previously mentioned, the experiment is based on the setup shown in Fig. 1. Thus, the optical sources DFB_1 and DFB_2 are connected to their respective Polarization Controllers PC_1, and PC_2. These controllers maximize the modulator output optical power. Each light beam is modulated by its respective $LiNbO_3$ Mach-Zehnder-Intensity Modulator MZ-IM_1 and MZ-IM_2. The Microwave Signal Generators MSG_1, and MSG_2 supply frequency signals $f_1$ = 2.37 GHz and, $f_2$ = 2.50 GHz, respectively, at an electrical power of 20 dBm. These signals are applied to the respective electro-optical modulator to modulate the laser light. The modulated optical beams coming from the Mach-Zehnder-Intensity Modulators are combined via an Optical Coupler (OC) 50:50 and injected into a reel of 25 km of Single Mode-Standard Fiber (SM-SF), whose characteristics are $a$ = 0.2 dB/km and $D$ = 16.75 ps/nm·km @ 1550 nm. At the output of the SM-SF, the light beam is inserted into the tunable OBP filter (Dicon, model TF-1550-0.8-9/9LT-FC/APC-1, Bandwidth: 1535 to 1565 nm). To select the desired optical signal, the OBP is directly tuned to the corresponding wavelength of each DFB, this is, $\lambda_1$ = 1548.26 nm or $\lambda_2$ = 1550.22 nm. Thus, when the OBP filter is adjusted to the $\lambda_1$ value, the signal

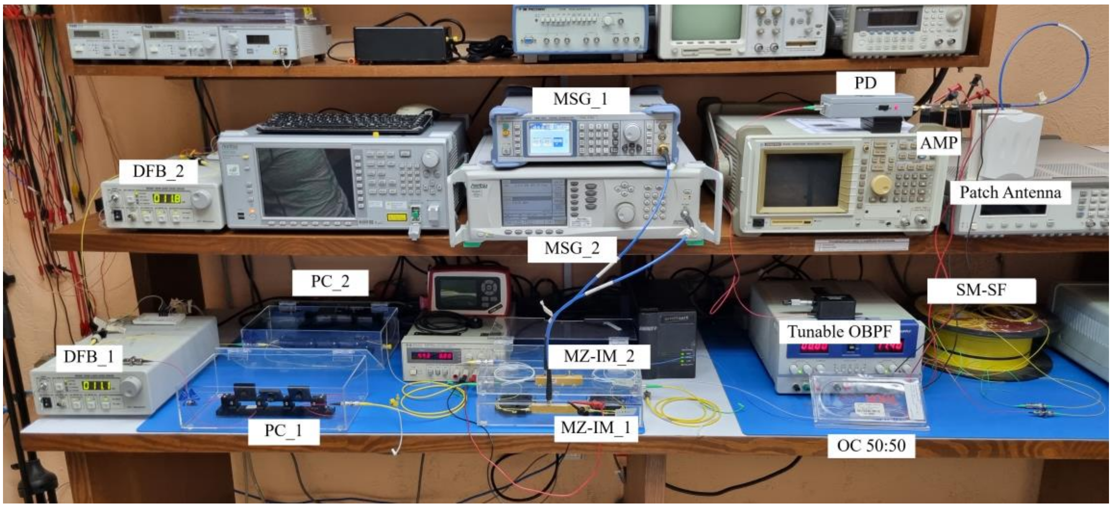

Fig. 4. Photograph of the experimental setup.

$f_1$ = 2.37 GHz is recovered, and when the filter is readjusted at the $\lambda_2$ value, the signal $f_2$ = 2.50 GHz is recovered.

The selected modulated optical signal ($\lambda_1$ or $\lambda_2$) is injected into the Photo-Detector (PD, Miteq, model: DR-125G, Bandwidth-13 GHz, $\Re$ = 0.9A/W) [33] providing its corresponding electrical signal ($f_1$ or $f_2$) which is amplified (ZVA-183-S+, 700-18000 MHz, and gain of 26 dB) [34] and connected to the directional patch antenna where it is radiated. The other directional patch antenna detects this radiated signal, amplifies it (ZVA-183-S+), and connects it to the Electrical Signal Analyzer (ESA, Agilent Technologies N9344C) for recording. The distance between the two antennas is 2 meters. The signal-to-noise ratio (SNR) parameter is adopted to evaluate the quality of each microwave signal.

Finally, Fig. 4 is a photograph of the experimental setup where the devices and equipment used in this experiment are indicated. The principle of operation of the photonics devices used in this work can be found in references [35, 36].

## 3. Discussion of Results

Figure 5 shows the registered microwave signals $f_1$ = 2.37 GHz, and $f_2$ = 2.50 GHz carefully recovered one by one by tuning the OBP to $\lambda_1$ = 1548.26 nm or $\lambda_2$ = 1550.22 nm, respectively. This graph shows the measured SNR value (level of the signal to the level of background noise). Due to the high SNR obtained, other wireless services that operate in the frequency range of 2.40 - 2.48 GHz, such as Radio-Frequency IDentification (RFID), ZigBee, WiFi, Bluetooth Low Energy (BLE), and Ultra-Wide Band (UWB) [37], are overshadowed and therefore are not detected in the registered microwave signals. From these signals, it is evident the significant separation of the noise floor, stability, and purity for the recovered MW signals.

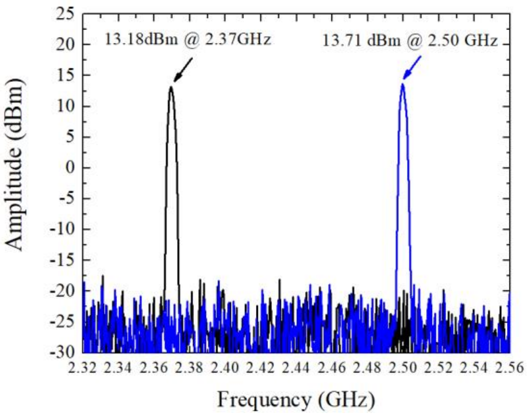

Fig. 5 Registered microwave signals $f_1$ = 2.37 GHz when the OBP is tuned at $\lambda_1$ = 1548.26 nm (black line), and $f_2$ = 2.50 GHz when the OBP is tuned at $\lambda_2$ = 1550.22 nm (blue line).

Table 1 summarizes the measured amplitude and SNR values corresponding to each wavelength.

Table 1. Measured amplitude and SNR values corresponding to each wavelength.

| | **$f_1$ = 2.37 GHz** | | **$f_2$ = 2.50 GHz** | |
|---|---|---|---|---|
| λ (nm) | Amplitude (dBm) | SNR (dB) | Amplitude (dBm) | SNR (dB) |
| **$\lambda_1$ = 1548.26** | 13.18 | 37.45 | | |
| **$\lambda_2$ = 1550.22** | | | 13.71 | 36.46 |

Although this proposal has been successfully validated for the case of two signals, this approach can be extended for more than two signals. In this regard, Fig. 6 illustrates the particular case for 4 signals using the appropriate Optical Couplers (OC). It is important to note that, due to the optical characteristics of the OBP filter, the wavelengths used must be near 1550 nm.

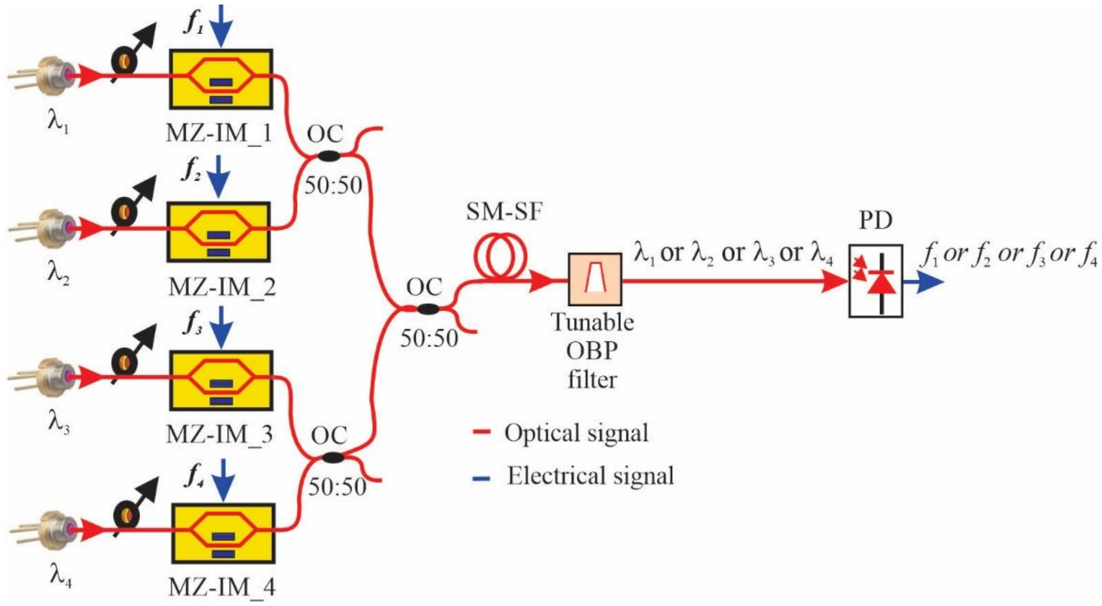

Fig. 6. Proposal to recover four different data signals sharing an optical link using a tunable OBP filter.

## 4. Conclusions

The purpose of this paper was to experimentally demonstrate a novel electro-optical setup that allows channel routing of microwave signals sharing the same optical link using a tunable Optical Band Pass filter. This setup enables subsequent indoor wireless transmission. The criterion used to validate the performance of this proposal was the measurement of the signal-to-noise ratio (SNR) value for each microwave signal. On average, an SNR = 37.01 dB was obtained. The high SNR indicates more signal than noise, ensuring high spectral purity for the obtained signals. Another performance metric to evaluate the quality of the microwave signals is measuring the phase noise of these signals. Taking advantage of the tuning range (1535 nm to 1565 nm), potentially, this proposal could allow the transmission of 30 different wavelengths that represent possible 30 users. The satisfactory of MW signals through 25 km of Single Mode-Standard Fiber was successfully demonstrated. This finding suggests potential applications in long-optical-range systems [38]. Potentially, microwave signals can be used as electrical carriers to transmit baseband information. In addition, this approach demonstrated the sharing of optical fiber among multiple users to deliver services via wireless links in indoor environments. It is well known that in a wireless indoor environment, the radiated signals can be affected by noise, interference, signal reflections on walls, furniture, people, etc. [39]. In this experiment, due to the short distance between antennas (2 meters), aligned to the point of view, these factors did not influence the measurements. A technical limitation of this proposal is that, unlike a WDM system, the recovery of each data signal is realized one at a time. Another limitation for transmitting 30 different wavelengths using the setup proposed in this work is the number of OCs employed. The fact that the OBP filter works at 1550 nm allows the standardization of its use and compatibility with other traditional techniques such as WDM, OTDM, POL-MUX, and SDM. Although this proposal was validated for the microwave S-band, this frequency interval can be extended to the maximum electrical bandwidth of the PD used.

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