# An Experimental Millimeter Wave Radio over Fiber Link with Double Polarization Multiplexing

**Nada Badraoui**
Budapest University of Technology and Economics: Budapesti Muszaki es Gazdasagtudomanyi Egyetem
**Tibor Berceli** ( berceli@hvt.bme.hu )
Budapesti Muszaki es Gazdasagtudomanyi Egyetem https://orcid.org/0000-0002-2003-6188

**Research Article**

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# An Experimental Millimeter Wave Radio over Fiber Link with Double Polarization Multiplexing

Nada Badraoui, Tibor Berceli,
Budapest University of Technology and Economics, Hungary
nada@hvt.bme.hu, berceli.tibor@vik.bme.hu

***Abstract* — A novel approach, an optical radio over fiber link with double polarization multiplexing is presented. In the two orthogonal polarizations of the optical beam the contents of information to be transmitted are different doubling the link capacity this way. For experimental verification a millimeter wave radio over fiber link with double polarization multiplexing has been developed. To ensure low cross polarization an incoherent approach is used. A high quality signal transmission is achieved by a proper procedure providing high polarization extinction ratio. In the experimental investigations different bit rates and fiber lengths are used. A signal with 12 Gbit/s bit rate is transmitted over a 25 km long link with about 1.10$^{-8}$ bit error rate. That result is much better than the already published data measured on experimental links.**

***Index Terms* — double orthogonal polarization multiplexing, cross polarization, polarization extinction ratio, polarization mode dispersion.**

## I. INTRODUCTION

The increasing demand for improving the service of present 5G and future 6G mobile networks requires signal transmission with higher capacity. The radio over fiber (RoF) link provides proper connections between a center station and its radio base stations in mobile networks.

Increasing the capacity of existing optical links is an important issue [1]. Presently for that, the polarization division multiplex (PDM) method is applied together with wavelength division multiplex (WDM) [2 - 3]. In that approach the optical beams at each wavelength have only one polarization, while the polarization of the adjacent channels is orthogonal. This way the wavelength difference between the adjacent channels can be reduced resulting in modest capacity enhancement.

The polarization division multiplexing technique has already been investigated in some publications [3 - 5]. Most of them were theoretical studies or simulations [6]. However, the combination of polarization division multiplex and wavelength division multiplex is a complex procedure, therefore it needs a relatively sophisticated system architecture.

Most of the papers considered applications for short distances at low radio frequency [7, 8], typically in the 2 GHz band with relatively low bit rates, usually 2.5 Gbit/s. However, in advanced systems higher bit rates are required. To achieve that goal the used radio frequency should be pushed to higher frequencies, mainly into the millimeter wave band.

In the present paper a novel approach, the double polarization multiplex (DPM) method is presented and investigated. In that case the optical beam has simultaneously two orthogonal polarizations or by other words it has double polarization. In the orthogonal polarizations of the beam the contents of information to be transmitted are different. The simulation results of the double polarization multiplexing approach in radio over fiber links are promising [9-11]. However, sufficient experimental investigations on these links have not been done in details yet.

An experimental link is presented in this paper to validate the usefulness and advantage of the double polarization multiplex approach applied in radio over fiber links. The polarization multiplexing method having two orthogonal polarizations at the same optical wavelength is introduced to double the capacity by transmitting two channels with different information [9 -11]. In this application the cross polarization between the two polarizations has to be kept at a very low level to avoid cross modulation between the two channels.

In this method there are two procedures to generate the optical wave with two orthogonal polarizations. In one approach a common optical source is applied for creating two optical information transmitting channels such a way that the optical beam is generated by a common laser source and it is divided in two equal parts. That means the two optical beams are coherent. In the other approach two independent optical sources are applied with the same wavelength. That means the two optical beams are incoherent. The incoherency helps to reduce the effect of cross polarization. In both cases the independence of the channels is only based on the polarization difference, i.e. on the polarization orthogonality. That means there is no need for optical filtering to combine and separate the two channels. In the following the incoherent approach is applied and investigated.

## II. EXPERIMENTAL MILLIMETER WAVE RADIO OVER FIBER LINK WITH DOUBLE POLARIZATION MULTIPLEXING

An experimental radio over fiber link using double polarization multiplexing has been developed and tested in the laboratory. Two independent channels were created by applying double polarization multiplexing. For this an optical beam was generated with very high polarization extinction ratio (PER). Based on our previous simulation results [9] we need at least 22 dB polarization extinction ratio (PER) in the transmitter. That means the intensity of the used polarization has to be 22 dB higher than that of the orthogonal polarization of the optical beam. That goal can be obtained by a suitable procedure.

The emitted laser beams usually have elliptical polarization. Therefore polarization controller is applied to get pure linear polarization by eliminating the smaller perpendicular polarization. The laser beam is passed through a linear polarizer plate in the polarization controller type PC-HP 8169A to create linear polarization. Then by the quarter wave (λ/4) and half wave (λ/2) plates the state of polarization (SoP) is adjusted. This way two independent orthogonal polarization states can be generated from the beam having pure linear polarization. The required polarization states can be created by proper procedures which are presented in the following.

*A./ Adjustment of polarization states*

The first step is the adjustment of polarization states. That is shown in Figure 1. The outputs of laser 1 and laser 2 are connected to a 3 dB directional coupler. This way we get their beams at the same output of the 3 dB directional coupler simultaneously. When the beam of laser 1 is adjusted, laser 2 is switched off. Similarly when the beam of laser 2 is adjusted, then laser 1 is switched off.

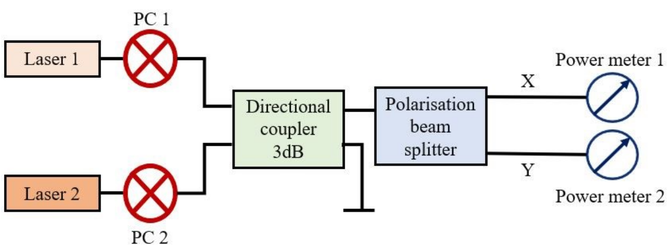



Figure 1. Polarization adjustment procedure

In the next step the beam of laser 1 with linear polarization is rotated by the polarization controller 1 (PC 1) to get maximum intensity at the X output of polarization beam splitter (PBS) and minimum at its Y output. There is 90° polarization angle difference between the two outputs. The same adjustment is done with the beam of laser 2. However, in that case by using polarization controller 2 (PC 2), minimum intensity has to be adjusted at the X output of polarization beam splitter and maximum of its Y output. With this procedure we get two optical beams with orthogonal polarization.

The polarization of the optical beams is adjusted with a similar procedure also in the other parts of the system. These procedures have to be carried out very precisely and the adjusted polarization states have to be kept unchanged during further investigations.

*B./ Independence of channels with double polarization*

The experimental investigations have to validate the expected behavior of the double polarization multiplex method. In the first step the independence of the two orthogonal polarization states is investigated by proper experiments. For that we apply the measurement set-up shown in Figure 2.

There are two optical sources with the same or almost the same frequency: 193.5 THz. Their output power is almost the same: 12 dBm and 13 dBm. The two optical beams are modulated by two random data streams in Mach-Zehnder optical modulators. The two modulated beams are adjusted by two polarization controllers to orthogonal polarization states. Then a polarization beam combiner (PBC) produces a combined beam with two orthogonal polarizations. That optical beam is transmitted over a single mode fiber (SMF) to the reception side. In the receiver a polarization beam splitter (PBS) separates the two polarizations.

These channels have been tested by measuring the bit error rate (BER) and eye diagram (EYE). In the experiment a common clock was used for the data sequences. This way the channels are synchronous which means a worst case test.

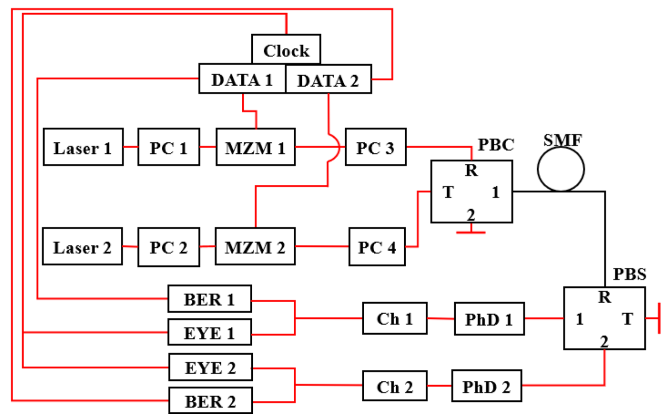



Figure 2. Block diagram of the experiment for checking the independency of channels with orthogonal polarization.

The notations are the following: PC = polarization controller, MZM = Mach Zehnder modulator, LO laser = local oscillator laser, PBC = polarization beam combiner, PBS = polarization beam splitter, SMF = single mode fiber, MMW = millimeter wave, PhD = photo diode, Ch = channel, BER = bit error rate, EYE = eye diagram.

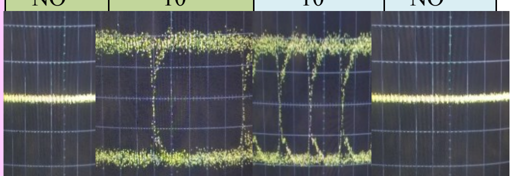
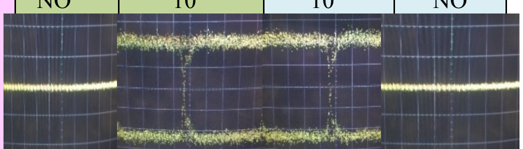
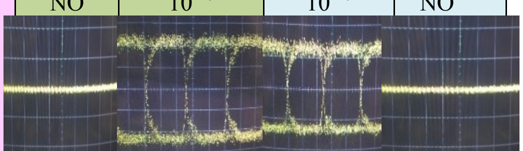
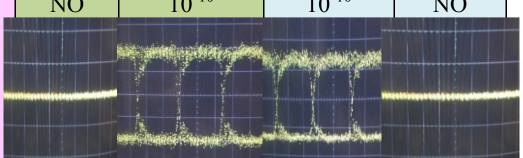
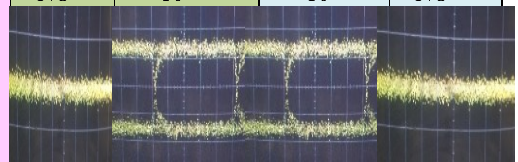
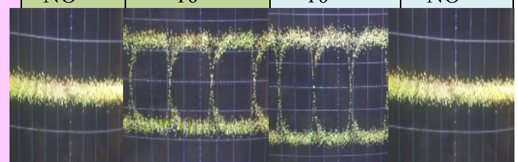
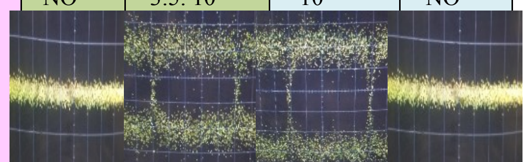
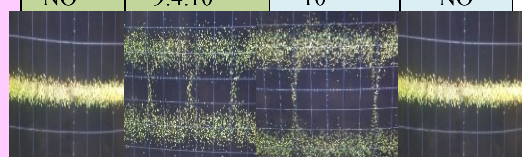
According to the block diagram we tested both channels separately. That means first channel 1 had no input signal while channel 2 had an input signal. In this case at the reception side in channel 1 we have to get only noise and negligible cross modulation from channel 2. Then we investigated the opposite version when channel 1 had an input signal and channel 2 was switched off. These cases were checked first without a long fiber, i.e. in a back-to-back arrangement. As can be seen in Table 1 there was no cross modulation to a channel in state OFF from a channel in state ON. In these cases we observed only noise in the OFF channels. That means there was no cross polarization effect.

Having done this basic measurement with different bit rates the investigation has been extended by applying fiber connections with different lengths between the transmitter and receiver. In every case the bit rate was varied between 1 Gbit/s and 12 Gbit/s. Then the eye diagram was tested along with the measurement of bit error rate. When the wave propagates along the fiber the original polarization extinction ratio is reduced due to the polarization mode dispersion (PMD). That results in bit error rate and eye diagram impairment as the fiber length is increased. The BER impairment is also dependent on the bit rate. Higher pulse broadening is obtained with increasing bit rate which is caused by the fiber chromatic dispersion. That influences the BER significantly.

As it can be seen in Table 1 there is no noticeable cross polarization effect even when using a 25 km long fiber with bit rate of 12 Gbit/s.

For the experimental radio over fiber link the Corning SMF-28e type fiber is used which has a relatively low chromatic dispersion coefficient at 1.55 μm wavelength: D = 12.5 ps/(nm.km), and the fiber attenuation is 0.2 dB/km.

Table 1. Measurement results of the base band optical link with double polarization multiplexing

| | | STEP ONE (laser 1: OFF, laser 2: ON) | | STEP TWO (laser 1: ON, laser 2: OFF) | |
|---|---|---|---|---|---|
| **Fiber length km** | **Bit rate Gb/s** | **Channel 1, BER** | **Channel 2, BER** | **Channel 1, BER** | **Channel 2, BER** |
| **Power dBm** | | **-35.78** | **-9.06** | **-6.88** | **-31.56** |
| **0 km** | 1 | NO | $10^{-9}$ | $10^{-9}$ | NO |
| | |  | | | |
| | 2 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 4 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 8 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 12 | NO | $10^{-10}$ | $10^{-11}$ | NO |
| **Power (dBm)** | | -26.51 | -8.12 | -6.43 | -27.40 |
| **1 km Loss 0.4 dB** | 1 | NO | $10^{-9}$ | $10^{-9}$ | NO |
| | |  | | | |
| | 2 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | |  | | | |
| | 4 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 8 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 12 | NO | $2.1.\ 10^{-9}$ | $1.6.\ 10^{-9}$ | NO |
| **Power (dBm)** | | **-28.20** | **-10.30** | **-8.36** | **-26.56** |
| **2 km Loss: 0.3 dB** | 1 | NO | $10^{-9}$ | $10^{-9}$ | NO |
| | 2 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | |  | | | |
| | 4 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 8 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 12 | NO | $7.7.10^{-9}$ | $9.1.10^{-9}$ | NO |
| **Power (dBm)** | | -29.05 | -10.20 | -8.49 | -32.47 |
| **7.045 km Loss: 2.9 dB** | 1 | NO | $10^{-9}$ | $10^{-9}$ | NO |
| | |  | | | |
| | 2 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | |  | | | |
| | 4 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 8 | NO | $10^{-10}$ | $10^{-10}$ | NO |
| | 12 | NO | $3.2.\ 10^{-9}$ | $3.4.\ 10^{-9}$ | NO |
| **Power (dBm)** | | **-34.50** | **-15.91** | **-14.25** | **-35.94** |
| **25.283 km Loss: 5.3 dB** | 1 | NO | $3.5.\ 10^{-8}$ | $10^{-9}$ | NO |
| | |  | | | |
| | 2 | NO | $9.4.10^{-9}$ | $10^{-9}$ | NO |
| | |  | | | |
| | 4 | NO | $8.2.10^{-8}$ | $10^{-9}$ | NO |
| | 8 | NO | $10^{-8}$ | $1.9.10^{-9}$ | NO |
| | 12 | NO | $7.7.10^{-8}$ | $9.1.10^{-9}$ | NO |

*C./ Radio over fiber link with double polarization multiplexing*

The aim of next experiment was to check the cross polarization effect in the radio-over-fiber link with double polarization multiplex arrangement. The block diagram of that experiment is presented in Fig. 3.

A local oscillator laser is inserted with 45° polarization angle compared to the two orthogonal polarizations. That beam can be decomposed into two parts: one half of the intensity is in the same polarization of channel 1 and the other half of the intensity is in the same polarization of channel 2. Very high frequency stability is necessary because two millimeter wave signals are generated at the reception side by mixing the beams of the two laser sources with the beam of the local oscillator laser working at 193.440 THz frequency. Then by optical mixing in the photo diodes the obtained mixing product is 60 GHz. These millimeter wave signals keeping the original information are then amplified, filtered and radiated from the radio base station to the subscribers.

The millimeter wave radio over fiber link was investigated by measuring the bit error rate and testing the eye diagram. In the experiment different bit rates and fiber lengths were used.

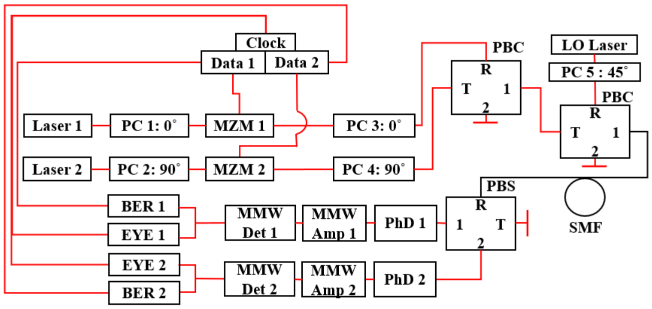
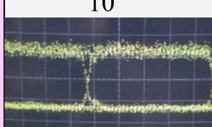
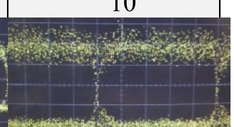
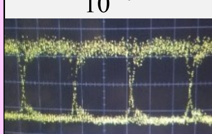
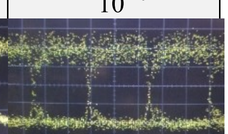
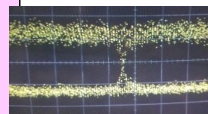
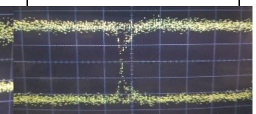
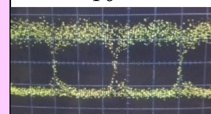
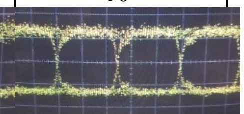
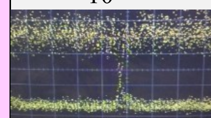
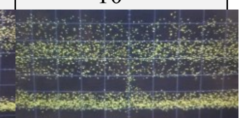
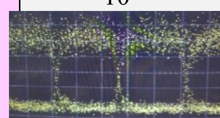
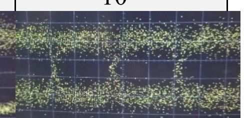
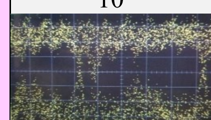
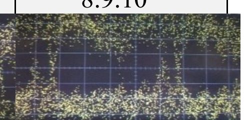
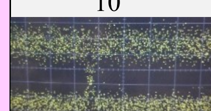
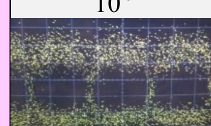
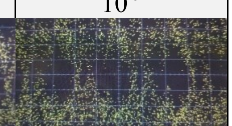



Figure 3. Block diagram of the radio over fiber link with double polarization multiplexing

The notations are the following: PC = polarization controller, MZM = Mach Zehnder modulator, LO laser = local oscillator laser, PBC = polarization beam combiner, PBS = polarization beam splitter, SMF = single mode fiber, MMW = millimeter wave, PhD = photo diode, Amp = amplifier, Det = detector, BER = bit error rate, EYE = eye diagram.

The measurement results of the millimeter wave radio over fiber link with double polarization multiplexing are presented in Table 2. Almost the same results are obtained in both channels having orthogonal polarization. That means there is no noticeable cross modulation effect between them. The eye diagrams are open also at higher bit rates. They are not presented in every case because no significant change was observed with increasing bit rates. However, with increasing fiber length a small deterioration is obtained both in the bit error rate and eye diagram. That is because of the effect of polarization mode dispersion which reduces the polarization extinction ratio. In spite of that as it can be seen in Table 2, a very good bit error rate of $1.2.10^{-8}$ was measured even for with 25 km long fiber transmitting a data stream of 12 Gbit/s bit rate. It is also worth mentioning that there is no need for optical filtering to combine and separate the two channels.

Table 2. Measurement results of the radio over fiber link with double polarization multiplexing

| Fiber length (km) | Bit rate (Gbit/s) | Channel 1 BER and eye diagram | Channel 2 BER and eye diagram |
|---|---|---|---|
| **Power (dBm)** | | **-7.10** | **-9.35** |
| **0 km** | 1 | $10^{-9}$ | $10^{-9}$ |
| | |  |  |
| | 2 | $10^{-10}$ | $10^{-10}$ |
| | |  |  |
| | 4 | $10^{-10}$ | $10^{-10}$ |
| | 8 | $10^{-10}$ | $10^{-10}$ |
| | 12 | $10^{-11}$ | $10^{-10}$ |
| **Power (dBm)** | | -6.41 | -7.79 |
| **1 km, loss: 0.4 dB** | 1 | $10^{-9}$ | $10^{-9}$ |
| | |  |  |
| | 2 | $10^{-10}$ | $10^{-10}$ |
| | |  |  |
| | 4 | $10^{-10}$ | $10^{-9}$ |
| | 8 | $10^{-10}$ | $10^{-9}$ |
| | 12 | $9.2. 10^{-9}$ | $9.9. 10^{-9}$ |
| **Power (dBm)** | | **-8.49** | **-9.85** |
| **2 km, loss: 0.3 dB** | 1 | $10^{-9}$ | $10^{-10}$ |
| | |  |  |
| | 2 | $10^{-9}$ | $10^{-8}$ |
| | |  |  |
| | 4 | $10^{-9}$ | $5.5. 10^{-8}$ |
| | 8 | $10^{-9}$ | $1.2. 10^{-8}$ |
| | 12 | $5.4.10^{-8}$ | $1.2.10^{-8}$ |
| **Power (dBm)** | | -8.30 | -10 |
| **7.045 km, loss: 2.9dB** | 1 | $10^{-9}$ | $8.9.10^{-9}$ |
| | |  |  |
| | 2 | $5.6. 10^{-9}$ | $9. 10^{-9}$ |
| | 4 | $8.5. 10^{-8}$ | $6.5. 10^{-8}$ |
| | 8 | $9.8. 10^{-9}$ | $3.8. 10^{-8}$ |
| | 12 | $2.1. 10^{-8}$ | $9.1.10^{-8}$ |
| **Power, dBm (dBm)** | | **-13.94** | **-15.54** |
| **25.283 km, loss: 5.3dB** | 1 | $10^{-9}$ | $10^{-8}$ |
| | |  |  |
| | 2 | $10^{-9}$ | $10^{-9}$ |
| | |  |  |
| | 4 | $9.01.10^{-9}$ | $8.9.10^{-9}$ |
| | 8 | $7.6.10^{-8}$ | $9.7. 10^{-9}$ |
| | 12 | $3.4. 10^{-8}$ | $1.2.10^{-8}$ |

## III. CONCLUSION

A novel approach, a radio over fiber link with double polarization multiplexing has been presented. In the two orthogonal polarizations of the optical beam the contents of information to be transmitted are different doubling the link capacity this way. For experimental verification a millimeter wave radio over fiber link with double polarization multiplexing has been developed. To ensure low cross polarization an incoherent approach has been used.

First an optical beam using baseband modulation in its two orthogonal polarizations was investigated experimentally for testing the cross modulation effect between the orthogonal polarizations. Then a millimeter wave radio over fiber link with two orthogonal polarizations was measured for checking its capabilities. It is worth mentioning that the independence of the channels is only based on the polarization difference, i.e. on the polarization orthogonality. That means there is no need for optical filtering to combine and separate the two channels. That function is performed by polarization beam combiners and splitters. In the experimental investigations different bit rates and fiber lengths were used.

A high quality signal transmission has been achieved by a special procedure providing high polarization extinction ratio. A signal with 12 Gbit/s bit rate was transmitted over a 25 km long link with about $1.10^{-8}$ bit error rate in both channels with orthogonal polarizations.

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## Figures

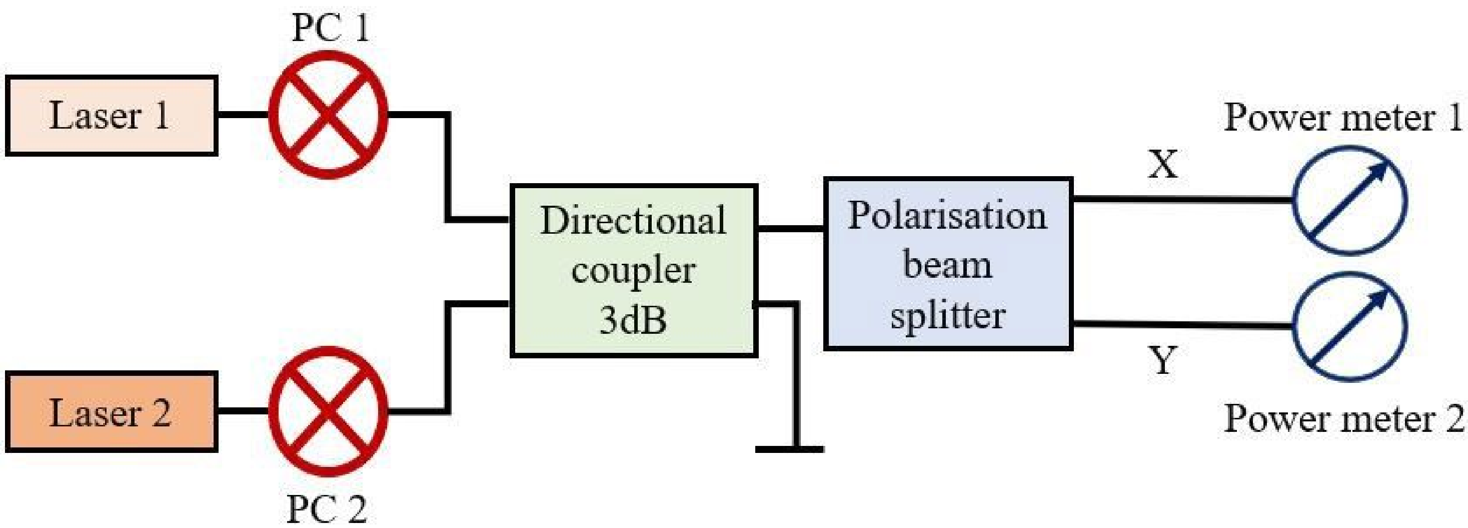


**Figure 1**

Polarization adjustment procedure.

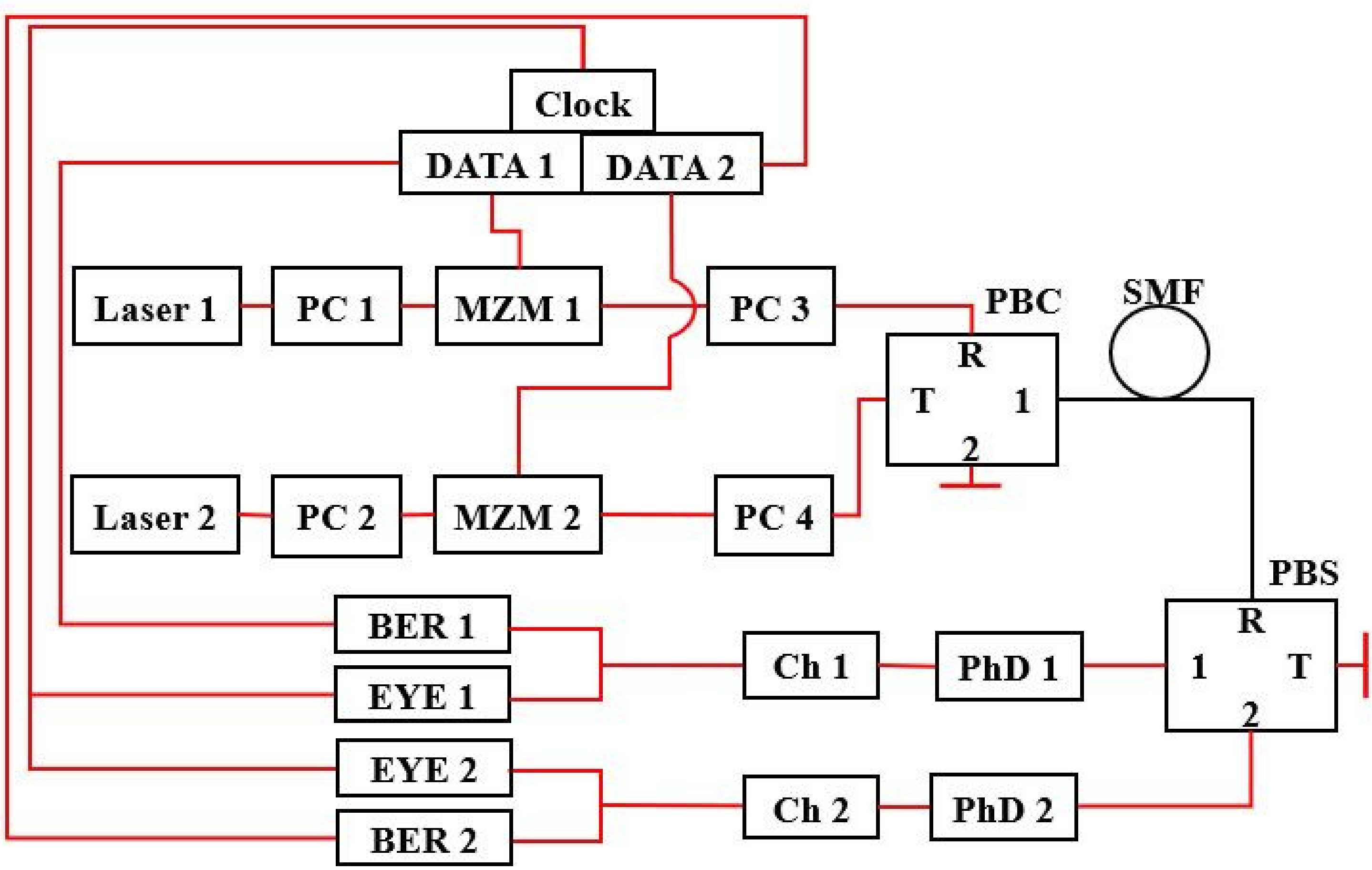


**Figure 2**

Block diagram of the experiment for checking the independency of channels with orthogonal polarization.

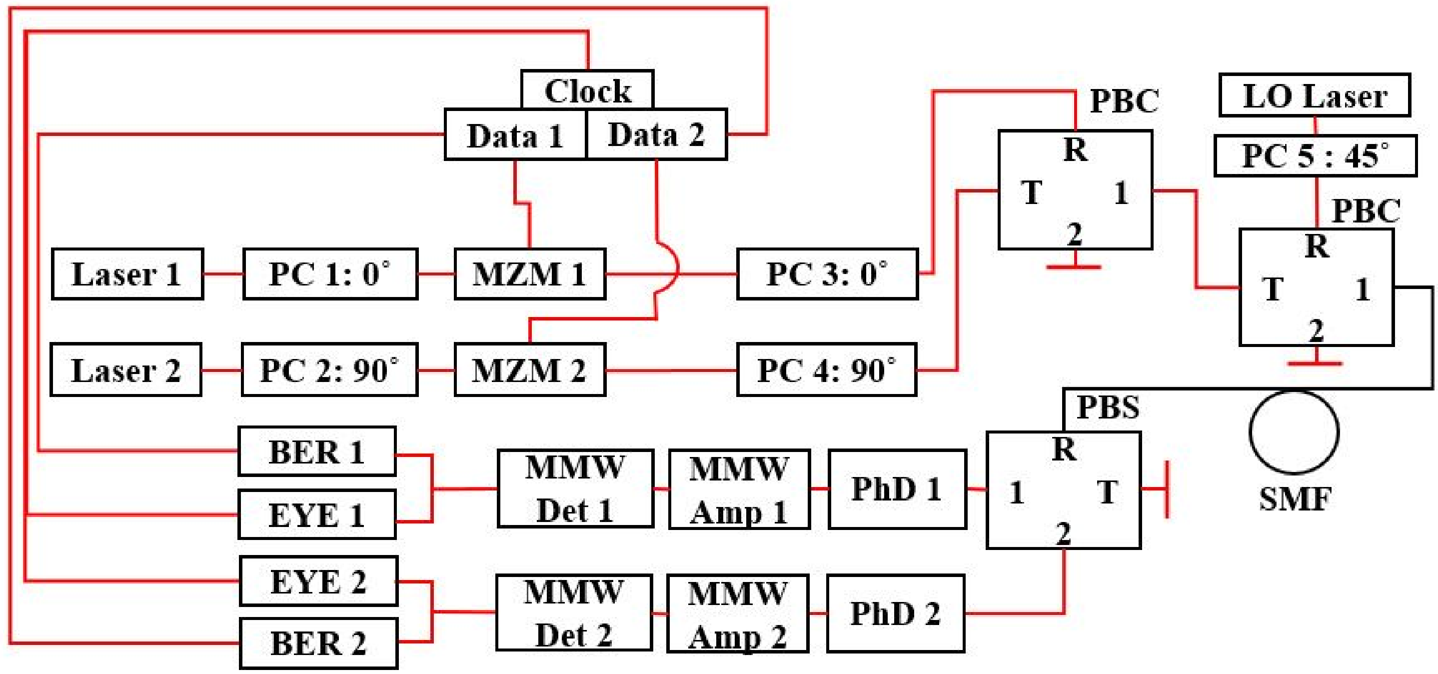


**Figure 3**

Block diagram of the radio over fiber link with double polarization multiplexing.