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# Simulation of Coherent Electromagnetic Waves in Wavelength Division Multiplexing (WDM) Transmission

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**Abstract**

This study analyzes the application of Wavelength Division Multiplexing (WDM) in fiber optic networks which aims to find the wavelength, WDM optical spectrum and modes, as well as the CPR estimated phase and modes. In this study WDM allows the simultaneous transmission of different data streams through a single optical fiber, using different wavelengths. This research was conducted using the python OptiCommPy module. This module is used to perform modeling of complex optical fiber transmission systems by considering the various parameters and disturbances involved in optical transmission. The results obtained from this study are that WDM networks can use full or limited wavelength conversion, depending on the wavelength conversion capability of each network node. Whereas multifiber networks use fiber pools between network nodes, and multifiber WDM networks can be implemented without or with full wavelength conversion. This research can be a guide for designing coherent electromagnetic waves in WDM transmissions using the OptiCommPy python module.

**Keywords:** Fiber Optics, WDM Networks, Wavelengths

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## INTRODUCTION

Fiber optics is a communications technology that can transmit data at speeds of several gigabits per second. In the future, fiber will be the distribution channel for thousands of channels of cable TV, telephone and video conferencing, distance learning, telemedicine, private cinemas, and so on. WDM technology is a transmission technology for transmitting various types of files (data, audio and video) transparently at the same time using different wavelengths in one fiber. Wavelength Division Multiplexing (WDM) allows the simultaneous transmission of different data streams over a single optical fiber network. There are two types of WDM technologies in use today: Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM) (*Multipleks Divisi Gelombang Dan Dense*, 2019).

CWDM allows up to 18 channels to be transmitted over a single dark fiber, while DWDM supports up to 88 channels. Both technologies are protocol independent, meaning any combination of data, storage, audio, or video can be used on different bandwidth channels. In terms of fiber, the main difference between CWDM and DWDM technologies is how the transmission lines are placed along the electromagnetic spectrum. WDM technology uses infrared light, which is outside the visible spectrum. Wavelengths between 1260 nm and 1670 nm can be used. Most fibers are optimized for two ranges, 1310nm and 1550nm, enabling an efficient "window" for the optical network (*Multipleks Divisi Gelombang Dan Dense*, 2019).

In previous studies it has been shown that OFDM can be applied in optical long-distance transmission systems and has many advantages over conventional single-carrier modulation formats (Lowery et al., 2006). Many of the major benefits of OFDM techniques have been studied and proven in the communications industry. First, the frequency spectra of the OFDM subcarriers partially overlap, resulting in high spectral efficiency. Second, the channel dispersion of the transmission system is easy to estimate and eliminate, and third, signal processing in OFDM transceivers can utilize efficient FFT/IFFT algorithms with low computational complexity. Recently, an equivalent optical domain multi-carrier format, called coherent optical OFDM (CO-OFDM) has been proposed for long-distance transmission (Shieh & Anthaudage, 2006).

In another study entitled “EDFA-WDM Optical Network Design and Development using OptiSystem Simulator” discusses data transmission using WDM for five optical channels in an optical transmission system. Data inputs with Laser signal are modulated before being multiplexed. Then, EDFA is used to encounter the effects of attenuation, distortion and Rayleigh scattering. The simulated transmission system have been analyzed on the basic of different parameters by using OptiSystem simulator, by simulating a model of communication system and using the most suitable settings of the system which include input power (dBm), fiber cable length (km) and attenuation coefficient (dB/km) at cable section, three different parameters will be investigated which are output power (dBm), noise figure (dB), and gain (dB) at receiver.

## METHOD

### WDM Network

All-optical (photonic) networks enable switching and routing functions at the optical layer. The optical signal still remains in the optical domain between the two access nodes and the latency caused by the optoelectronic conversion at the intermediate node disappears. In an all-optical network, various types of multi-user technologies can be used: OTDM (optical time division multiplex), CDM (code division multiplex), or WDM (wavelength division multiplex). WDM is the favorite choice because both CDM and OTDM are still limited by the physical characteristics of the fiber and optical technology conditions, especially because of the difficult synchronization requirements (Bahleda & Blunar, 2008).

Optical networks, which use wavelength division multiplex technology are called WDM networks. They provide simultaneous transmission at several different optical wavelengths over the same optical fiber. However, thanks to multiple connections being simultaneously shared on the same fiber, the enormous bandwidth potential of optical fiber is better utilized. This allows different end users to operate at electronic processing speeds, which are still limited to around 40 Gb/s (Bahleda & Blunar, 2008). In addition, each connection made between end nodes on a WDM channel allows for different specifications of bit rates and data formats. This is referred to as WDM transparency. All connections using the same fiber link must allocate different and different wavelengths. It is also known as the constraint of using different wavelengths.

The proposed model is designed for a wavelength-directed optical network based on optical channel switching. The network consists of two types of nodes :

- Optical cross-connects (OXCs) equipped with multiple input and output ports, which connect to other OXCs or optical access nodes with optical fiber
- End nodes (access nodes), which provide the interface between the nonoptical end and the optical system.

The OXC can be equipped with an optical converter to provide optical conversion in the optical domain. If the OXC does not support any wavelength conversion, the same wavelength must be used in the next line jump. This is known as the wavelength continuity constraint (Murthy & Gurusamy, 2002). If all network OXCs do not support any wavelength conversion, the same wavelength must be used on all fiber links along the physical path. Such a circuit is called no wavelength conversion network (Murthy & Gurusamy, 2002). Connection requests are accepted only if there is at least one wavelength simultaneously free on all links along the path. This means that calls can be blocked even if there are free wavelengths on all links, but not all of them are the same.

The maximum number of wavelengths is still limited by the technology of the optical device, the total available bandwidth, the spectral range of the components, and the distance between the channels. Hence the reuse of wavelengths is required by the conversion of wavelengths in OXC. If OXC allows wavelength conversion, a different wavelength can be assigned at the next line jump. If every OXC supports full wavelength conversion, it is referred to as a full wavelength conversion network. Connection requests are accepted if there is at least one free wavelength on each fiber link along the path.

Full wavelength conversion in the optical domain improves network blocking performance significantly (Murthy & Gurusamy, 2002). Unfortunately, the use of full-wavelength conversion all-optical converters at each network node greatly increases network costs due to the technological complexity of optical devices. The researchers' goal is to achieve high or similar network performance with a limited wavelength conversion range for each converter, a limited number of converters in each OXC, and a limited number of OXCs supporting wavelength conversions throughout the network. Another possibility to relax wavelength continuity constraints is to implement multifiber splices.

**Limited wavelength conversion network**

If the network supports wavelength conversion with some restrictions, it is called a limited wavelength conversion network. These restrictions can be as follows (Murthy & Gurusamy, 2002):

- Limited range of wavelengths to which input wavelengths can be converted. If any of the incoming wavelengths can be converted to any wavelength from a finite set of $k$ outgoing wavelengths at the output side of the spectrum field of wavelength $W$, it is referred to as a finite wavelength conversion with degrees of $k$ conversion;
- a number of wavelength converters placed at each node. This is also known as partial wavelength conversion. A wavelength converter bank consisting of a collection of several wavelength converters used together. Convertible wavelength share-per-node and share-per-link switch architectures have been proposed (Murthy & Gurusamy, 2002);
- a number of nodes that allow wavelength conversion are placed in the network. If only some network nodes have wavelength conversion enabled, not all, it is called sparse wavelength conversion (Murthy & Gurusamy, 2002).

The first two limitations mentioned above are implemented in network nodes and the last one is based on network restrictions. Network costs can be reduced by using converters with a limited wavelength conversion range rather than full range conversion, assuming a limited number of converters at each node and a limited number of conversion nodes in the network rather than enabling wavelength conversion. on each network node. However, the placement of converters in the network, the allocation of converters in a node, and the specification of the wavelength conversion range issues are raised. Recent studies have shown that limited conversions are much easier and cheaper than full conversions. In addition, a finite wavelength conversion network is still capable of providing enough conversion to use the channel efficiently, and at a much better channel efficiency than a network without wavelength conversion, depending on the design.

In general for a finite wavelength conversion with k conversion degrees, any wavelength $\lambda i$, $I \in W$ can be converted to any wavelength $\lambda j$, $j \in k$ from a finite set of k ($1 < k < W$) wavelengths exiting the output side of the spectral plane full wavelength W (Bahleda, Blunar & Bridova., 2004). In practice, the following types of finite wavelength conversions are used:

- symmetric: each incoming wavelength can be converted to the wavelength of d adjacent outgoing wavelengths on the left and right sides of the spectrum wavelength plane, as well as the same wavelength. This means that each incoming wavelength can be converted to one of $k$ = 2$d$ + 1 outgoing wavelength;
- nonsymmetric: each incoming wavelength can be converted to the same wavelength or to the left (or right) side of the wavelength field. This means that it is possible to change the incoming wavelength to the outgoing wavelength from $k = d + 1$ wavelength.

Note that optical OXC conversion capabilities can be classified into three types depending on their wavelength conversion range $k$ :

i. $k = 1$, no wavelength conversion capability;
ii. $1 < k < W$, limited wavelength conversion capability;
iii. $k = W$, full wavelength conversion capability.

**Multifiber Network**

Networks that use fiber pools between network nodes are called multifiber networks. In a multifiber WDM network, each link consists of many fibers and each fiber carries information at many wavelengths (Bahleda & Blunar, 2008). Generally, each network link can consist of a different number of fibers $F$, and each fiber can use a different number of wavelengths $W$.

Thanks to the declining cost of fiber in recent years, current research is leaning towards multifiber networks. In fact, most of the optical networks used to date, use multiple fibers between end nodes because of the economic benefits of laying fiber pools for the purposes of fault tolerance and future network growth. Improved performance, in terms of blocking probability and throughput, can be achieved by using these fibers or adding more fibers to an existing system.

Theoretically, multifiber WDM networks can be implemented without, limited, or full wavelength conversion. However, the benefits of using multifiber networks without wavelength conversion are important. If the wavelength cannot be continued on the next hop on the same fiber, and the same wavelength is available on another fiber on the next jump, then the incoming wavelength can be transferred to another fiber. Thus the function of a multifiber network with F fibers per link and W wavelengths per fiber is equivalent to a finite degree F wavelength conversion of a single fiber network, with F.W wavelengths (Bahleda & Blunar, 2008)

The design goal of a multifiber network is to decide how many fibers per link are needed to guarantee high network performance or to achieve high network performance with a minimum number of fibers per link..

**WDM transmission system with CO-OFDM**

The basic WDM CO-OFDM transmission system is shown in Fig. 1. A generic CO-OFDM system consists of an OFDM transmitter, an optical link and an OFDM receiver. In an OFDM transmitter, the input data bits are mapped to the corresponding information symbol of the subcarrier in a single OFDM symbol, and a digital time domain signal s(t) is acquired using IFFT (Hara & Prasad, 2003):

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{k=Nsc} c_{ik} \prod \; (t - iT_s) \exp j2\pi f_k \, (t - iT_s) \qquad (1)$$

$$f_k = \frac{k-1}{t_s} \qquad (2)$$

$$\prod(t) = \begin{cases} 1, & (-\Delta_G < t \le t_s) \\ 0, & (t \le -\Delta_G, t > t_s) \end{cases} \qquad (3)$$

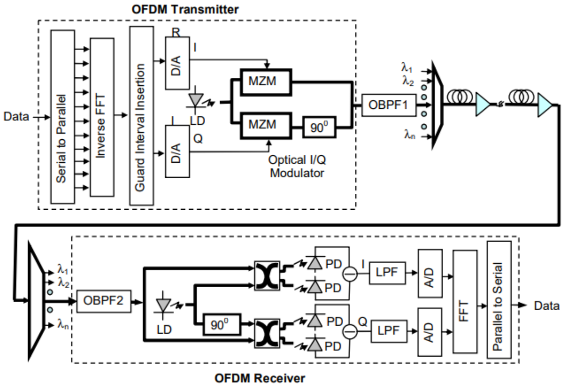



**Figure 1.** CO-OFDM System Concept Diagram

Where *Cik* is the ith information symbol in the *kth subcarrier*, *fk* is the frequency of the *subcarriers*, *Nsc* is the number of OFDM *subcarriers*, *Ts*, *ΔG*, and *ts* are the OFDM symbol period, the length of the guard interval and the observation period respectively. In order to reduce the transmitter and receiver bandwidth efficiently, the *subcarrier* frequency of the OFDM symbol is preferably between $-f_{BW}/2$ and $f_{BW}/2$, where $f_{BW}$ is the bandwidth of the OFDM symbol [8]. A popular form of baseband OFDM signal, *s(t)* can be generated as

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=-Nsc/2+1}^{k=Nsc/2} c_{ik} \prod \ (t - iT_s) \exp j2\pi f_k \ (t - iT_s) \quad (4)$$

The digital time domain signal *s(t)* is then inserted with a guard interval and converted into a real time waveform through a *digital-to-analogue converter* (DAC) (Hara & Prasad, 2003). then the guard interval is to eliminate interference between symbols *inter-symbol interference* (ISI) and the length of the interval *ΔG* must meet the requirements :

$$\Delta_G \geq \frac{c|D|Nsc}{f^2 t_s} \quad (5).$$

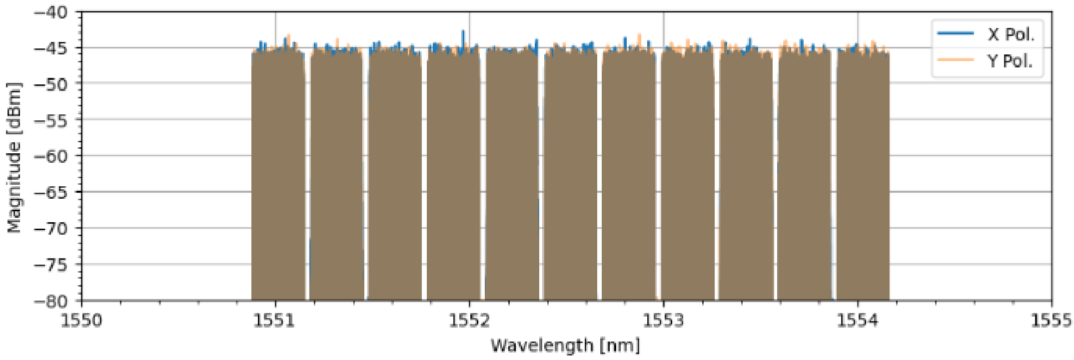
Where *f* is the optical carrier frequency, *c* is the speed of light, *Dt* is the total accumulated chromatic dispersion in units of ps/pm, and *Nsc* is the number of OFDM *subcarrier*. Electrical to optical OFDM conversion is achieved by applying the real and imaginary components of *s(t)* to ports I and Q of the optical I/Q modulator, respectively. Two biased *Mahnch-Zender* (MZ) optical modulators at zero output power and a 90 degree phase shift were used (Bao & Shieh, 2007). Multiple WDM channels with CO-OFDM modulation format are rolled out to the optical link. The optical link consists of multi-span SSMF fibers and *Erbium doped fiber amplifiers* (EDFA) to compensate for fiber transmission loss. In contrast to conventional link designs, CO-OFDM systems may not use any dispersion compensated fibers. WDM channels are demultiplexed and detected using two optical coherent detectors that act as optical-to-mains OFDM I/Q converters. In the OFDM receiver, the OFDM signal will be sampled using the ADC, and demodulated by performing an FFT to recover the data.

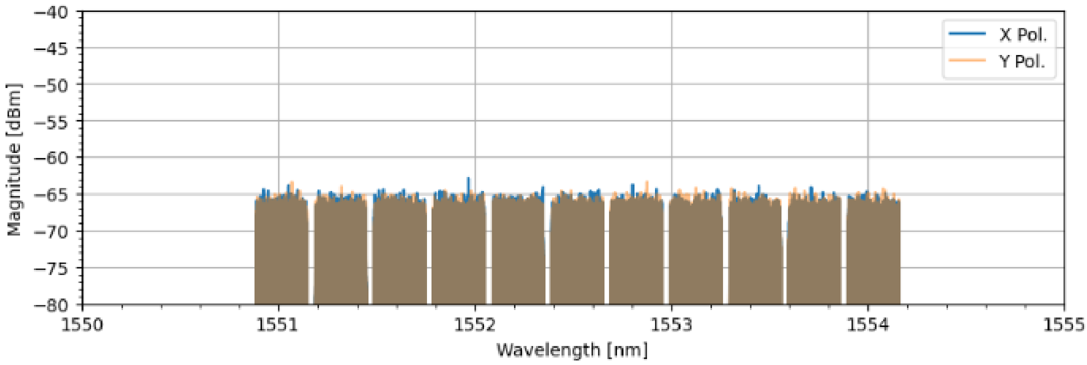
## RESULTS AND DISCUSSION

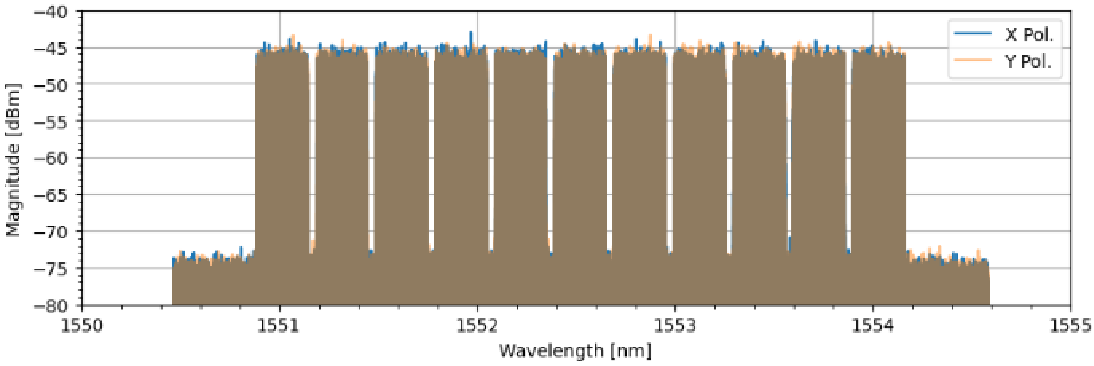
Simulations were carried out to find the wavelength, WDM optical spectrum and modes, as well as the estimated CPR phase and modes. The coding result is a simulation implementation of WDM (Wavelength Division Multiplexing) transmission using the OptiCommPy module. This module is used to perform modeling of complex optical fiber transmission systems by considering the various parameters and disturbances involved in optical transmission. In a previous study, an analysis of the effect of the EDFA amplifier in a WDM transmission system based on different parameters has been carried out. By simulating the communication system model and using the most suitable system settings which include input power (dBm), fiber cable length (km) and attenuation coefficient (dB/km) in the cable section, three different parameters will be investigated namely output power (dBm), noise figure (dB), and gain (dB) at the receiver (Kawal et al., 2012).

We applied commonly used system parameters to our simulation which resulted in: OptiCommPy being successfully installed using the pip package manager. The installed version is OptiCommPy 0.3.0. After the installation is complete, several calculations or analyzes are carried out using OptiCommPy, processing of modulated optical signals with an average power of 6,941 mW or the equivalent of 8,414 dBm, then other modulated optical signal processing is carried out with an average power of 0,069 mW or the equivalent of -11,586 dBm, followed by measuring several parameters such as forward pump power (25,000 mW), reverse pump power (0,000 mW), average power after amplification by the receiving amplifier (6,808 mW or equivalent to 8,331 dBm), and gain gain (19,917 dB). Then demodulation with a center frequency (fc) of 193.1000 THz or a wavelength (λ) of 1552.5244 nm. Finally, measuring the performance of the demodulated signal such as SER (Symbol Error Rate), BER (Bit Error Rate), SNR (Signal-to-Noise Ratio), EVM (Error Vector Magnitude), MI (Mutual Information), GMI (Generalized Mutual Information) ), and NGMI (Normalized Generalized Mutual Information). The results of these measurements are given in the relevant units and include information for X and Y polarizations.

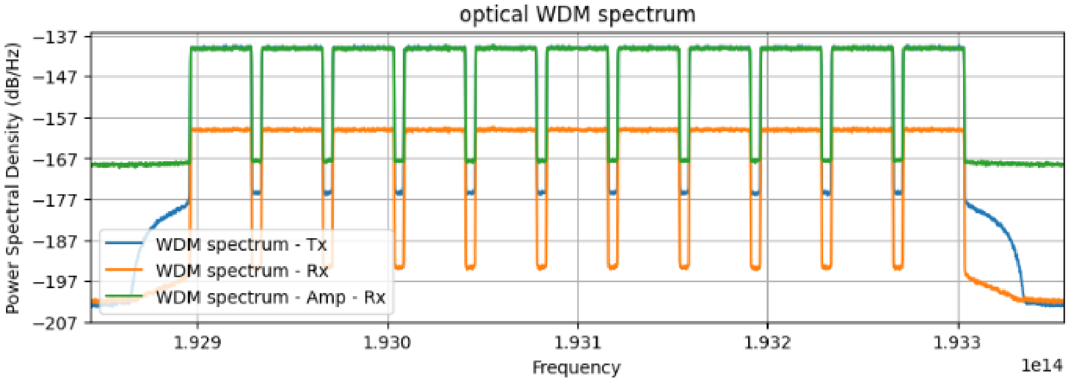
- Generated wave graphs

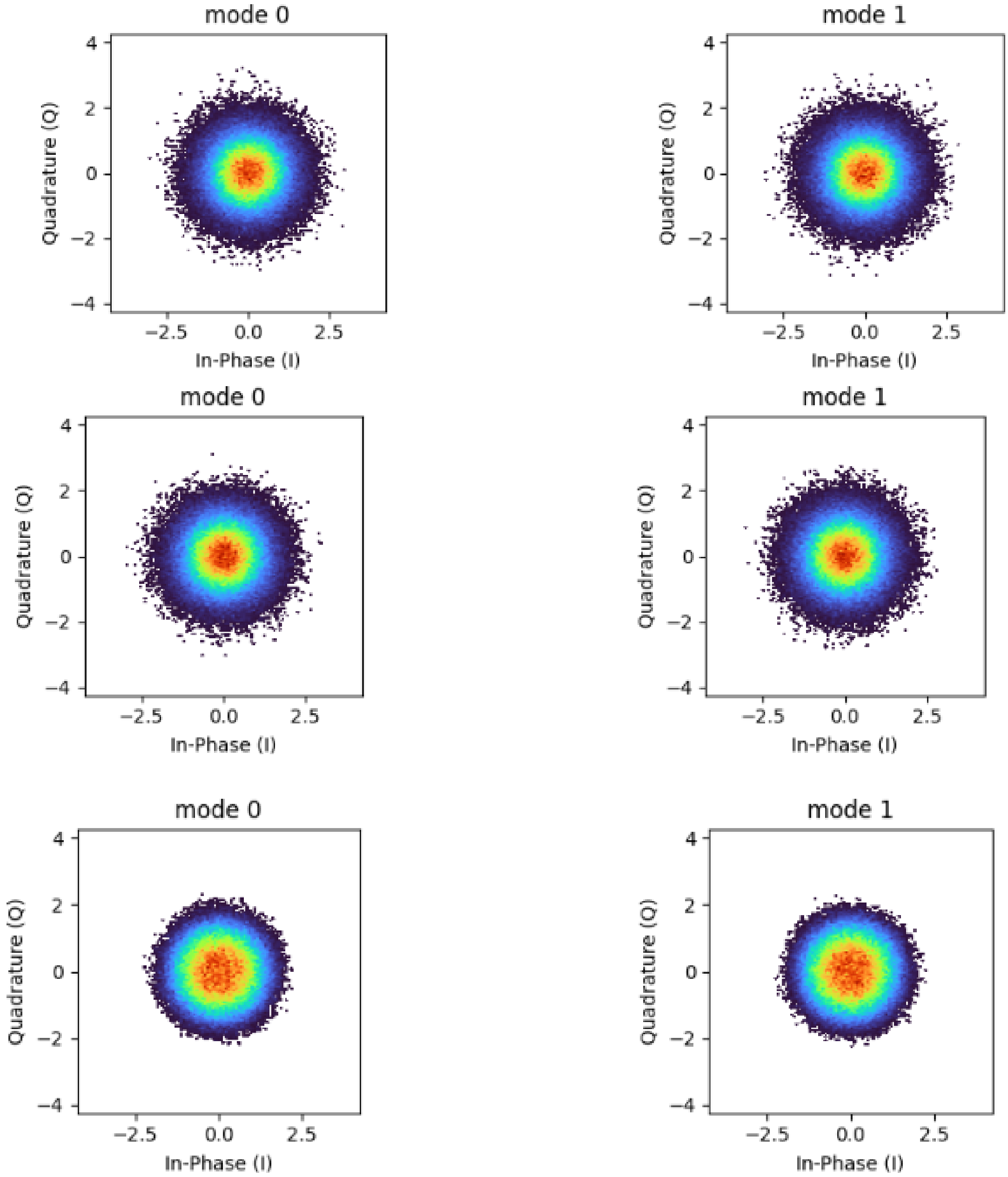


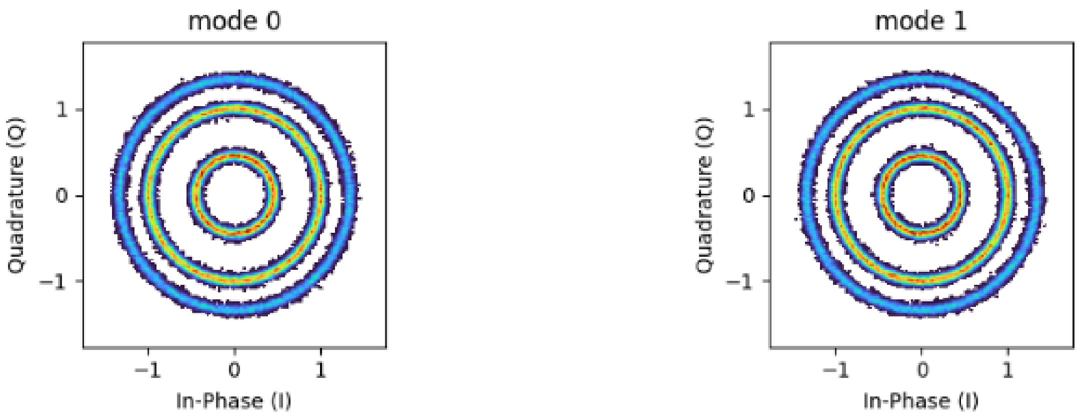



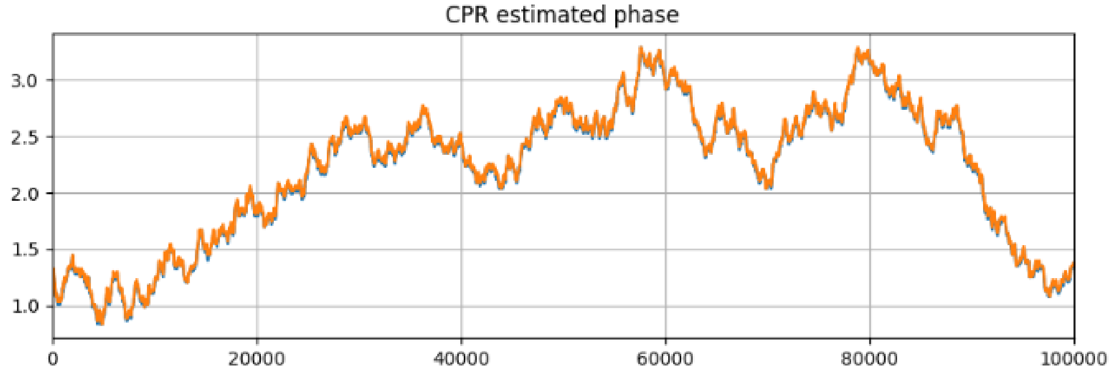

- Graphical optical WDM spectrum and the resulting modes


optical WDM spectrum
Power Spectral Density (dB/Hz)
−137
−147
−157
−167
−177
−187
−197
−207
WDM spectrum - Tx
WDM spectrum - Rx
WDM spectrum - Amp - Rx
1.929
1.930
1.931
1.932
1.933
Frequency
1e14


mode 0
mode 1
mode 0
mode 1
mode 0
mode 1
Quadrature (Q)
In-Phase (I)
4
2
0
−2
−4
−2.5
0.0
2.5




- Graph of the CPR estimated phase and the resulting modes :



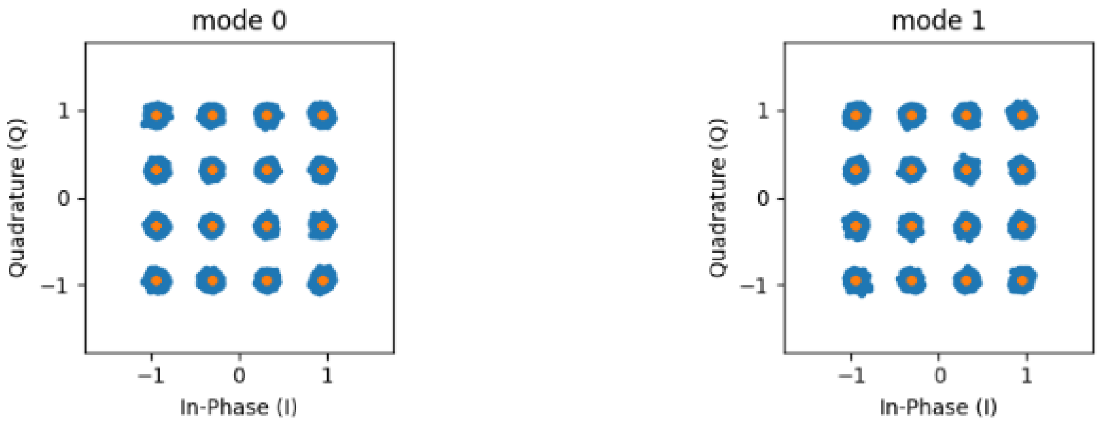




**Table 1.** WDM Transmission Simulation Results

| | Pol. X | Pol. Y |
|---|---|---|
| SER | 0.00e+00 | 0.00e+00 |
| BER | 0.00e+00 | 0.00e+00 |
| SNR | 26.69 dB | 26.70 dB |
| EVM | 0.21 % | 0.21 % |
| MI | 4.00 bits | 4.00 bits |
| GMI | 4.00 bits | 4.00 bits |
| NGMI | 1.00 | 1.00 |

## CONCLUSION

Fiber optic or optical fiber is a communication technology that can transmit data at high speed and WDM (Wavelength Division Multiplexing) technology allows simultaneous transmission of different data streams over a single optical fiber network. There are two types of WDM technologies in use today, namely CWDM (Coarse Wavelength Division Multiplexing) and DWDM (Dense Wavelength Division Multiplexing). WDM networks allow different end users to operate at higher electronic processing speeds. An optical network using WDM technology is called a WDM network, which provides simultaneous transmission at several different optical wavelengths over the same optical fiber. WDM networks can use full or limited wavelength conversion, depending on the wavelength conversion capabilities of each network node. Whereas a multifiber network uses fiber pools between network nodes, and a multifiber WDM network can be implemented with no, limited, or with full wavelength conversion.

## RECOMMENDATION

This research still requires follow-up experimentally for the future in order to get more significant results. Besides that, innovation and more references are still needed as a basis for continuing this research.

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