From Light to Information-the Optical Fibres: The Backbone of High-Speed Data Transmission

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Abstract: Optical fibre sensors are designed majorly for detecting and gauging various parameters. These sensors provide different benefits over traditional sensors, making them more valuable in different applications. They are capable to detect very small changes in actual parameters to measure in case of biosensing. With this sensitivity, they can detect subtle changes in pressure, strain, temperature, vibration, refractive analytes, and other factors with utmost accuracy. They enable remote sensing. As light sensors can carry data, it is possible to place sensing elements at unreachable or distant sites and still convey the data back to core monitoring system without degrading signals. To increase bitrate, this study was focused on transmission of "Optical Time-Division Multiplexing (OTDM)" at 80Gbit/s to optimize the change in phase between opposing OTDM channels. With limited capacity of fibre, there is a need to increase spectral efficiency and use amplitude, phase, and polarization for transmission of signals. Over the years, various approaches and configurations have been proposed to improve sensitivity of sensors based on optical fiber. However, it is believed that selecting the configuration of optical fiber sensors must be chosen as per certain application. As these sensors keep on improving and evolving, they play a vital role in control applications and monitoring around several industries.

Keywords: *Optical Time-Division Multiplexing, OTDM, Optical Fibre Sensors, Bitrate, High-Speed Data.*

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I. INTRODUCTION

There has been a lot of advancements on biological and chemical sensors in research over the past three decades (Butt et al, 2023). A lot of research is being conducted on developing systems which can detect a lot of analytes for clinical, security, and environmental purposes in a sample (Haider et al, 2020). Optical sensors can probe coatings of surface with different optical phenomena while achieving high sensitivity and low noise, giving a lot of promise in this aspect (Butt et al, 2022). They also enable real-time measurements and in-situ sensing while providing benefits of speed.

Remote sensing, multi-analysis, and miniaturization are additional uses for optical sensors (Butt et al, 2022). Optical sensor systems are less likely to produce explosion in a toxic environment as compared to electrical transduction and are different from "electromagnetic (EM) interference" (Kazanskiy et al, 2022). Optical biosensors don't have a lot of benefits over lab-based systems, when it comes to other sensing systems (Zhu et al, 2021). Fibre optics is based on the concept of "total internal reflection (TIR)", enabling correlation between assessment of light intensity at the target concentration and detector (Butt, 2022).

To interact with specified analyte, bio-receptors like antibodies, enzymes, and oligonucleotides can be halted at the core of fibre (Mulchandani et al, 1999). After establishing the standard curve, this interaction affects the characteristics of sensitive layer and can be related to concentration of analyte. Biosensors in fibre optics can have high resistance, sensitivity, high sensitivity, rapid detection, and real-time tracking and are modest with EM interference (Butt, 2022). These qualities are helpful for biosensors as they can discretely and concurrently focus light of different wavelengths. They can be used to detect analytics with different probes of DNA (Hengoju et al, 2022; Xie et al, 2023).

Optical fibre sensing can make the most of interaction among properties of fibre and light for reliable and accurate measurements. Some of the sensors in optical fibre work on various systems, such as, "Fabry-Perot sensors, Bragg-grating sensors (FBGs), Raman scattering-based sensors, interferometric fibre sensors, optical time-domain reflectometry (OTDR), Brillouin scattering-based sensors, evanescent wave sensors, optical frequency domain reflectometry (OFDR) and polarimetric sensors." FBGs are episodic changes in refractive index at the core of optical fibre. With exposure to temperature or strain changes, the wavelength of light or Bragg wavelength changes (Chen et al,

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2023). This change helps in measuring pressure, temperature, strain and other parameters.

Fabry–Perot interferometers rely on a thin film or reflective surface to make an interference pattern among reflected and incoming light. Because of pressure, strain, or changes in temperature, gap among reflective surfaces can be tracked to evaluate the sensor parameters (Spammer et al, 1996). Interference patterns are used by interferometric fibre sensors in the light passing through optical fibre. It may cover "Michelson interferometers and Mach–Zehnder interferometers" where changes in properties of optical fibre may cause changes in phases in the waves of interfering light (18).

When light works with fibre molecules, Raman scattering takes place, resulting in a change in wavelength relative to strain or temperature. Brillouin scattering consists of interaction among acoustic and light waves in the fibre. In the scattered light, the change in frequency gives data about changes in strain and temperature along the fibre (Muanenda et al, 2019). The OTDR technique relies on backscattered light to determine optical fibre properties, which is widely used for sensing events like bends and fibre breaks (Shatalin et al, 1998). Changes are measured in polarimetric sensors in polarization of light passing through optical fibre (Mermelstein, 1986).

Polarization may be altered with changes in strain, temperature or other parameters, determining these quantities. Small amount of light can be exploited with evanescent wave sensors which go beyond the optical fibre core. By enabling the interaction between light and nearby environment, it is important to measure the changes in refractive index (Jiao et al, 2020). The frequency response of optical fibre can be measured with OFDR along its length. It offers high-resolution capacities of different parameters like temperature and strain (Liang et al, 2021).

These techniques provide various levels of suitability, spatial resolution and sensitivity for different uses. Fiber sensing keeps on evolving and innovating sensor performance and design. Optical fibre biosensors have been through major advances over the years, providing different benefits for different applications (Singh et al, 2023). Significant progress has been reported in researches to improve detection limits and sensitivity of biosensors in optical fibre. It can be made possible by developing novel sensing systems, including "localized surface plasmon resonance (LSPR)" and "surface plasma resonance (SPR)" enabling very sensitive detection of analytes at least amounts (Zhang et al, 2023; Wang et al, 2022).

Functionalization has evolved to improve specificity and selectivity of biosensors used in optical fibre (Du et al, 2023). Immobilizing certain biomolecules and other approaches on fibre surface or adopting nanomaterials enable detection of analytes like DNA, pathogens, and proteins (Li et al, 2022). Miniaturization is an essential area to advance in optical fibre sensors. Researchers can fabricate optical fibre up to few micrometers, enabling adoption of microfluidic devices (Shi et al, 2022). Miniaturization promotes point-of-care testing, portability, and helps in vivo sensing (Liang et al, 2023). In optical fibre biosensors, progress has been made in developing multiplexed platforms (Yin et al, 2023; Khonina et al, 2022).

With various sensing elements or principles in an individual fibre, it can detect various analytes at the same time. It has been applied in environmental monitoring, food safety, and medical diagnostics (Lyu et al, 2022). It is important to improve biocompatibility and stability of biosensors in optical fibre to integrate into biological solutions. Surface changes and coatings have been established to minimize biofouling, stable sensor, and reduce interactions with samples to ensure long-term and reliable operation (Cruz and Fangueiro, 2016; Meunier et al, 2023; Li et al, 2023). Biosensors used in optical fibre provide imaging and real-time monitoring. With "optical coherence tomography (OCT)" approaches or imaging fibre, it is possible to track and imagine dynamic changes and biological processes in amounts of analytes in real-time (Lee et al, 2013).

It is possible to integrate optical fibre biosensors with "lab-on-a-chip" solutions to create a portable, highly efficient, and compact platforms. This integration helps in sample analysis, processing, and handling in a device, making the sensing process easier. There are different applications of sensors in different fields like environmental tracking and biomedicine. They can detect biomarkers in physical fluids, determining water quality, tracking levels of drug in patients, and identifying pollutants in the air (Cai et al, 2023).

In optical fibre sensors, these advancements have a lot of potential to improve diagnostic potential for improving efficiency and accuracy and real-time monitoring of environmental and biological sensors. There is a need to consider two important strategies as per how the structure of fibre waveguide can be used. First includes changing properties of inner waves with a specific type of optical fibre. Second method consists of application of processing and handling to the overall structure of optical fibre to change the shape of guiding wave. As optical fibre is used so widely, "single-mode fibre (SMF)" and "multi-mode fibre (MMF)" have been combined into individual structure to reduce the cost of sensor (Rahmani et al, 2022; Smith, 1978).

On the other hand, various structures of special fibre with controllable model, easy integration, and constructing properties, covering "multi-core fibre (MCF), polymer optical fibre (POF), hollow core fibre (HCF), and photonic crystal fibre (PCF)" made and recommended for different purposes of plasmon detection (Savović et al, 2023; Kiroriwal and Singal, 2024; Shih et al, 2023; Arroyo et al, 2023). For evanescence waves, it is very difficult to reach cladding surface as light of incident travels in the core of fibre, which is enclosed in the cladding. Because of this, it is commonly needed to change the shape of fibre optic structure with a unique technique of processing to disrupt the original mode of optical transmission.

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A lot of fibre architectures like "D-shaped fibre, tapered optical fibre (TOF), and U-shaped fibre" have made entry over the years (Gupta and Kant, 2018; Liu et al, 2020; Johari et al, 2022). To realize several architectures of optical fibre, Specialized machinery is needed for optical fibre processing. There are several benefits of plasmonic sensors based on optical fibre over traditional sensors, including remote sensing, miniaturization, high sensitivity, and ability to perform monitoring in real-time (Butt et al, 2023). Applications are found in various fields like biomedical diagnosis, monitoring in the environment, chemical analysis, and food safety.

It is worth noting that adoption and development of plasmonic sensors based on optical fibre consists of complex fabrication. In addition, selecting sensing elements, plasmonic materials, and detection approaches may vary by certain application needs. For low-dose detection of analyte, the plasmonic sensitivity should be better with increasing demand for sensory applications, majorly in clinical, life science, food safety, and medical fields.

In the detection system, detection range and sensitivity can be improved with "surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR)" technologies. A fibre probe, light source, and spectrometer are important parts of fibre optics system based on SPR/LSPR. The light flow generates the evanescence waves provoking the interaction between sensor and metal layer. The enhanced effectiveness of coupling between surface plasmon (SP) and evanescent waves rely majorly on fibre, probe geometry, wavelength of light, and metal layer. Optimizing the immobilization effects and shape of fibre waveguide are two of the most effective ways to improve the overall SPR/LSPR performance of sensing (Ren et al, 2022; Li et al, 2022; Zhang et al, 2022).

Even though optical fibre is a highly broad way for transmission of information, it is evidently impossible to moderate the complete optical bandwidth. Since optical signal is generated initially from the pattern of electrical data, it is transformed back to the digital signal to transmit to recover the transmitted data. The limited bandwidth of majority of opto-electronic and electronic components sets the limit on the optimum optical bitrate. For instance, maximum binary bitrate of 56Gbit/s can be achieved with existing "pulse pattern generators (PPGs)" (Makovejs, 2011).

When it comes to achieve optimum information, current attempts consist of Wavelength Division Multiplexing (WDM) where the entire C-band or optical bandwidth is broken into disjointed bands (Mitra and Stark, 2001). When these modulated channels are combined, it is possible to achieve very high optical capacity (Cai et al, 2010; 2011). The signal of WDM is demultiplexed at the receiver back into the channels which are individually modulated with a tunable optical fiber for measuring "bit error rate (BER)" (Figure 1a).

OTDM is the alternative to WDM to improve the overall capacity of information (Figure 2b). It is a strong tool helping to overcome the limitation of opto-electronic and electronic components to improve the bitrate of transmission signal. While WDM increases the overall capacity of transmitter in frequency domain, the OTDM depends majorly on time domain. OTDM majorly depends upon various data streams in the time domain (40Gbit/s) to achieve up to 80Gbit/s or 160Gbit/s. The signal is distributed at the receiver into multiple channels of base-rate for BER measurements.

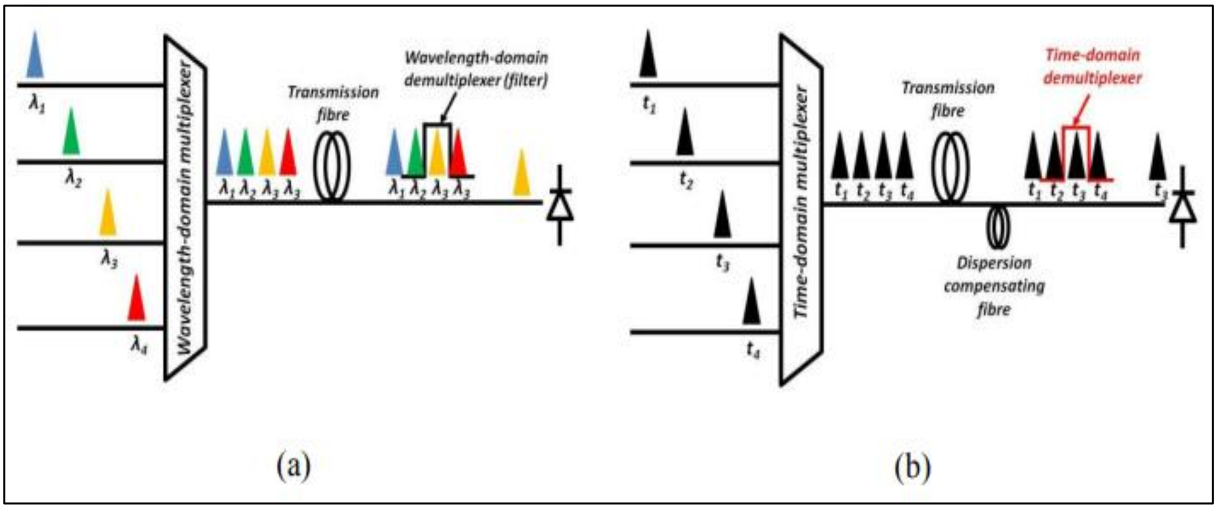

Fig 1 A Representation of (a) WDM Transmitting Signals through Transmission Fibre and WDM Filter; and (b) 3-Domain Multiplier for OTDM Signal Reception
Source: Makovejs (2011)

II. LITERATURE REVIEW

Hasegawa (2004) discussed theoretical development in transfer of data in optical fibre with special focus on application of solutions and non-linear effects in a comprehensive review and tutorial. A significant growth has been achieved in distance and amount of data transfer with optical fibers with rapid growth of fiber manufacturing, theoretical knowledge, and ultra-high-speed devices during the 1990s. It covered fundamentals of Lightwave broadcast

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of fibers, introduction of several solutions and problems as per optical solutions, and derivation of equation describing data transfer.

The future of wireless communication has been revolutionized by the new paradigm of “visible light communication (VLC)”. The visible light spectrum of 400 to 700 nm is modulated with transmission of data in VLC for illumination. The potential of VLC is observed in experimental and analytical work to provide transmission of high-speed data with added benefits of improved communication and energy efficiency. VLC is still in infancy as only a few articles have published and addressed the research in physical layer. Rehman et al (2019) have discussed the perspectives of a system while surveying existing challenges and literature for integrating and implementing VLC.

A lot of research studies have focused on “polymer optical fibre (POF)” for around 20 years because of unique characteristics offering the potential for exciting and new applications and they are overwhelmed with increased losses. Theodosiou and Kalli (2020) discussed efficient sensing of polymer with “perfluorinated polymer fibers”. They also reviewed latest advancements related to “Bragg grating” in multimode gradient index, proposing characterization for various applications and measures.

There have been rapid emergence of new applications and data services in wireless transmission, especially mobile broadband, which need to improve user experience. There are several challenges for current RFID based wireless systems to cope with sophisticated, varied, and bandwidth hungry applications. With “license-free spectrum”, the ever-changing “optical wireless communications (OWC)” technology, an inherently high transmission rates and security is observed as a possible alternative to wireless communications based on radio frequency for long- and short-distance applications. Ghassemlooy et al (2016) provides an insight to focusing of OWC system on the current status and past development, along with intended and current areas of application.

O'Keeffe et al (2015) gives an insight to recent developments related to radiotherapy dosimetry while focusing majorly on developing dosemeters in optical fibers for radiotherapy, based on *in vivo* uses. There are several benefits of optical fibers over traditional approaches for radiotherapy, due to their immunity to electromagnetic signals, small size, and suitable for multiplexing and remote tracking. Along with being flexible and light, small aspects of dosemeters are minimally invasive and best suited for “*in vivo* dosimetry.” For instance, it is possible to place the sensor in the patient for brachytherapy. Monitoring of tumors can be done by placing the optical fibers in the tumor itself or around critical tissues through needles or applicators for real-time information. They discussed the major applications for sensor design with some major weaknesses and strengths related to developing those techniques.

- *Subsystem Design with OTDM 80Gbit/s*

For OTDM transmitter, using “short return-to-zero (RZ) pulses” is the most important requirement rather than traditional “non-return-to-zero (NRZ)” pulses for carrying the information of binary signal. As the RZ pulse energy is focused in the time window shorter than small period, the separation of time between two successive pulses can be used effectively for multiplexing various data streams (Figure 2). Hence, there is a certain need for the pulse width. The shorter the width of the pulse, the more streams of data could be multiplexed in the same way (usually known as “full-width half-maximum (FWHM)”). The pulse width must be less than 2ps to complex four data streams of OTDM signal, i.e., from 40Gbit/s to 160Gbit/s, to avoid huge decline of signal because of crosstalk in time channel from overlapping wings of opposite pulses after multiplexing (Weber and Nakazawa, 2007).

Figure 2(c) illustrates enhanced crosstalk between OTDM signals when pulse width is not that short. To determine the width of short pulses, it is possible to use intensity autocorrelator. One can achieve more in-depth data about phase profile and pulse intensity with advanced techniques for pulse measurement, including “frequency resolve optical gating (FROG)” (Trebino et al, 1997). To overturn the cross-talk in time-channel and interferometric noise because of changing difference of phase across nearby OTDM channels, extinction ratio of around 35 to 40dB can be ensured with a transmitter (Jepsen et al, 1998). For extinction ratio, the need is minimized for OTDM tests with phase control applicable bit wise or a bit-by-bit basis as the impact of fluctuating phase is cancelled between OTDM channels.

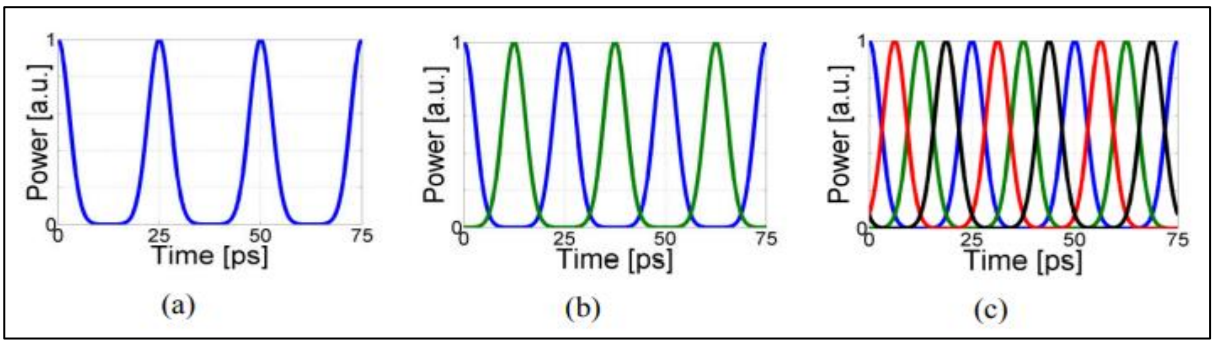

Fig 2 Higher Bitrate Binary Signal Generated with OTDM Technique (a) Signal with 40Git/s Base Rate; (b) with 80Gbit/s Base Rate; and (c) 160Gbit/s Base Rate
Source: Makovejs (2011)

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It is possible to obtain a short-pulse train with a "mode-locked laser diode (MLLD), consistent wave (CW), or mode-locked fibre ring laser (ML-FRL)" carved externally with "Mach-Zehnder modulator (MZM) and electro-absorption modulator (EAM)". In case of outer pulse to slice a cascade of multiple modulators, it can reduce the pulse width. The importance of 160Gbit/s bitrate was observed from the 4-fold rise in bitrate, increasing the potential upgrade to 160Gbit/s from 40Gbit/s. It is also possible to generate sub-picometer pulses with different techniques of pulse compression (Kroh et al, 2006).

- *Designing OTDM Multiplexer*

There are different techniques to multiplex the RZ base-rate signal into higher OTDM signal. To generate OTDM signal for 80Gbit/s, the first way can be distributing RZ optical pulse of 40GHz with two different MZMs or EAMs and two different data patterns. Then, the RZ signals of 40Gbit/s are inserted on a temporary basis related to one another by around 50% of period with adaptable line of delay. In optical powers, the residual change in two arms of interferometer is stable with tunable attenuator. Then two RZ-OOK signals of 40Gbit/s were recombined with a 3dB coupler to achieve the OTDM signal of 80Gbit/s (Figure 2a). It is possible to achieve various OTDM levels for higher bitrate of 160Gbit/s or 320Gbit/s. Till date, 1.28Tbit/s is the highest bitrate of OTDM achieved with "on-off-keying (OOK)", direct detection, and "polarization division multiplexing (PDM)" and PDM, coherent detection, and modern modulation formats can be achieved with 10.2Tbit/s (Richter et al, 2011).

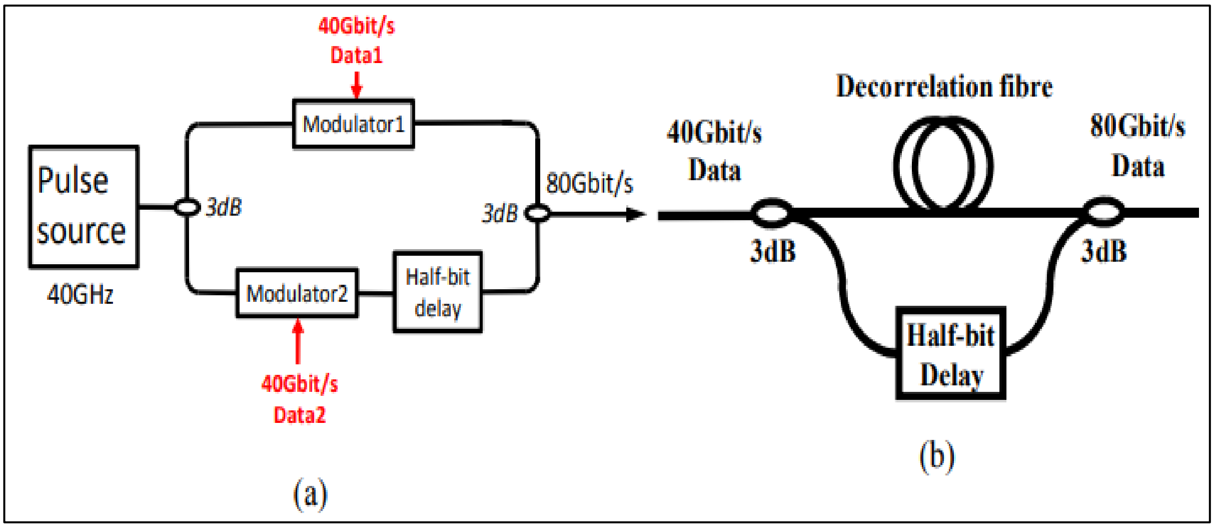

Fig 3 A schematic Illustration of OTDM Signal of 80Gbit/s Generated with (a) Individual Patterns of Electrical Data; (b) Delay-Line Multiplexer
Source: Makovejs (2011)

The process of generating OTDM signal in transmission labs could be simplified with delay-line interferometer and single modulator to synthesize OTDM signal (Figure 3b). This experimental technique is accepted widely among scholars and emulates OTDM transmitter behavior, which includes individual modulators. The interferometric delay-line system also means that same data is carried by two OTDM tributaries, which represents the behavior of actual transmitter. It is possible to reduce the spectral amount of non-decorrelated sequences in comparison to that of actual "pseudo-random binary sequence (PRBS)" and they will result in estimate of overall performance of the system (Figure 4) (Boivin and Chraplyvy, 2000).

It is possible to decorrelate two of the 40Gbit/s tributaries of OTDM within multiplexer with replacement of difference of optical paths for two signals. Inserting a piece of fiber is one of the most common ways to implement in interferometer arms to delay one signal optically (Figure 3). To retain actual PRBS structure of sequence generated, the relative delay should be equal between OTDM channels to half the length of the pattern of initial sequence (Kaminow et al, 2008).

Table 1 Length of Optical Fibre Needed to Decorrelate Various Patterns of PRBS

Pattern	2^7	2^9	2^{11}	2^{15}	2^{23}	2^{31}
Fibre	32 cm	1.28m	5.12m	81.92m	20.97km	5368.7km

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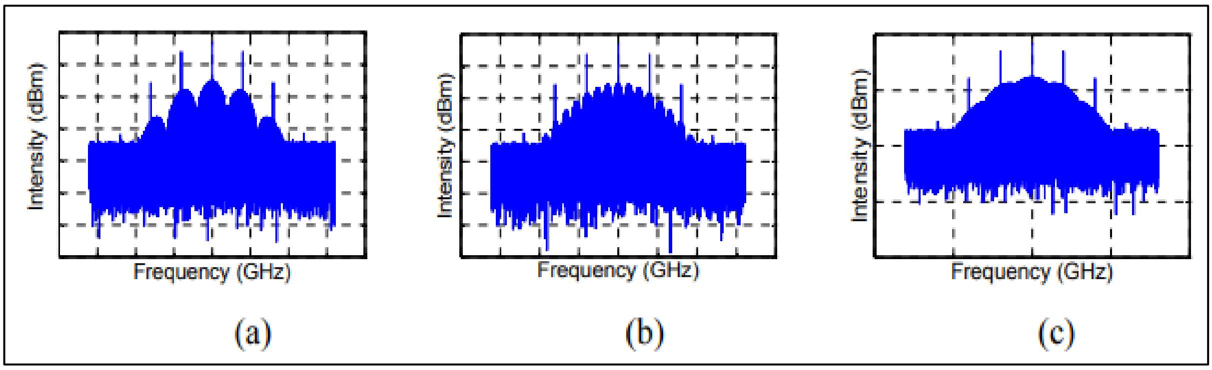

Fig 4 RF Spectra Simulated for OTDM Signal of 80Gbit/s; (a) No Decorrelation of OTDM Channel; (b) Decorrelation (2bit); and (c) Half Decorrelation of PRBS
Source: Boivin and Chraplyvy (2000)

Since the needed decorrelation fibre length needed rises up with pattern length, it is quite impractical to completely decorrelate long patterns of PRBS (Table 1). Along with it, difference should not exceed between two interferometer arms and coherence length of laser to enable coherent interference needed to generate bitwise signals. In addition, full decorrelation is needed for one bitrate at once and it also limits flexibility. Even the modest decorrelation is enough to distribute transitions of signal and this experimental technique is widely accepted among several studies (Molle et al, 2009; Zhou and Yu, 2009).

Inability to manage “optical phase” among opposite OTDM channels is one of the possible issues of traditional multiplexer, making it harder to adopt modulation formats on the basis of fixed stage relations. It arises with the fact that deviations of ambient temperature can cause random difference of optical path within the multiplexer of fibre delay and it causes random changes among opposing channels of OTDM. Wavelength drift of laser is another cause of phase changes. Both drift of wavelength and temperature adversely affect interferometers with short range of free spectral.

Various techniques could control the stage between opposite bits, including optical free-space arrangement with “planer Lightwave circuit (PLC)” technology and EAMs (Kagawa et al, 2008; Schilling et al, 2002). For OTDM transmitter, developing prototype can be costly and needs a lot of expertise in fabrication and device design.

- *Designing OTDM Receiver*

An 80Gbit/s of OTDM and over traditional receiver cannot detect OTDM signal because of limited bandwidth at the receiver. Demultiplexing OTDM signal before sending the same to receiver of 40Gbit/s is the solution, where it is possible to measure the BER directly. In OTDM experiments, the clock recovery should provide timing for demultiplexing and clock signal to measure BER. To experiment with detecting switching window, it is possible to demultiplex with “cross-phase modulation (XPM)” or “four-wave mixing (FWM)” effects in “semiconductor optical amplifier (SOA)” (Schubert et al, 2002; Mortimore, 1988; Verdurmen et al, 2004).

These consist of “gain-transparent ultrafast nonlinear interferometer (GT-UNI), non-linear optical loop mirror (NOLM), and hybrid integrated symmetric Mach-Zehnder (HI-SMZ)” interferometer. Currently, NOLM is the only technique demultiplexing OTDM signal of around 640Gbaud, corresponding for OOK to 640Gbit/s (Weber et al, 2005). For DPSK or OOK signal, information was carried by one symbol about just 1 bit. One symbol includes two bits of information in a DQPSK modulation, which refers to double DQPSK bitrate of its symbol. On the other hand, EAM is used by easier technique, driven by electrical signal recovered at the receiver and it can also generate a switching window.

At the demultiplexer, there are two or more EAMs like transmitter design that can be flowed to minimize width of window. Even though demultiplexer based on EAM can be simple to adopt and compact, the problem is limited width of window and window of switching cannot be tuned. Hence, there is a need to design the switching window for a specific bitrate. With coherent detection, pulse local oscillator is can delay and demultiplex the interested channel. The CRU design should be adjusted in traditional “non-OTDM tests”. A “voltage-controlled oscillator (VCO)” can be used to realize the “clock recovery unit (CRU)” with high Q-filter or phase comparator to extract clock from the spectrum directly.

Several methods have been proposed like using “nonlinearity in SOAs, phase-locked loop with comparators, bi-directionally EAM, and phase-locked loop with high-Q filter (Boerner et al, 2003; Kamatani and Kawanishi, 1996; Turkiewicz et al, 2005). A traditional receiver can be used after down-conversion from OTDM to base rate. Such receiver includes 40GHz photodetector in the broadband, as per the front-end of error detector and added broadband RF amplifier of 40GHz should be used. It is possible to use optional stage of noise loading to set the “signal to noise ratio (OSNR)”. It usually includes attenuator and added “Erbium doped fiber amplifier (EDFA)” to manage the launch power.

- *Optical Fibre Sensors - Working Mechanism*

Before working mechanism, there is a need to understand increasing proliferation of optical fiber sensors, especially in a developing country like India, beating China in terms of population density. India’s push for large-scale internet connectivity is increasing the spread of optical fiber

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across rural and urban settings. With flagship programs like BharatNet and Digital India, the government is investing drastically in fiber development, building optical fiber as a significant medium for both backhaul connectivity and access. Telecom operators roll out "fiber-to-the-tower and fiber-to-the-home (FTTH) services with major capital investment and public private partnerships (PPP)". These initiatives promote high-capacity, low-latency networks needed for digital services like e-commerce, online education, and telehealth.

Alongside, user demand is rising significantly for high-bandwidth settings, such as, virtual collaboration, cloud platforms, and video streaming. Organizations are moving towards cloud-based solutions, which need scalable and robust connectivity. Network operators are designing upgradable and scalable fiber structures to meet demands in future. Over 1.75 million km of optical fiber network has been built since 2018 in order to connect more than 250,000 institutions, reflecting commitment of India to inclusive growth of broadband network and reliable infrastructure (Market Research Future, 2025).

In 2025, the optical fibre cable market was estimated at US$0.55 billion in India and is projected to cross US$1.03 billion by the year 2031, rising at 11.03% of CAGR (Figure 5). "Optical Fiber Cables (OFC)" are cutting-edge media for data transmission using light signals for providing video, voice, and high-speed internet services. In comparison to copper services, OFC acts as a foundation of modern infrastructure with lower latency and excellent bandwidth in applications across data centers, 5G network, telecom, and smart cities. With the rapid growth of digital ecosystem, there is a widespread demand for high-performance data transfer. Apart from the 5G rollout and increasing use of internet in remote areas, government programs like BharatNet and Digital India propel the rise of fiber networks. Their infrastructure is scaled by telecom operators, while foreign bodies are improving innovation and local production in fiber network to further promote market growth (Research and Markets, 2025).

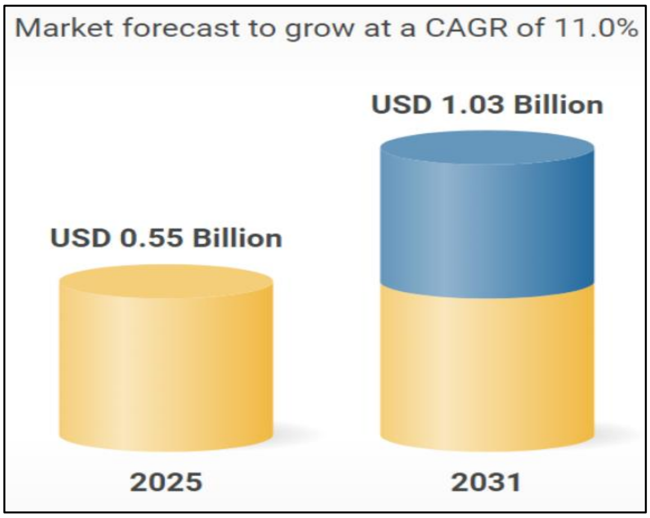

Fig 5 Broadband Market Projections by 2031
Source: BCC Research (2024)

The market signifies a dynamic and major landscape defined by consistent expansion and innovation. Transmitting data rather than electric currents through light signals, these sensors have gained immense popularity because of their immunity and precision to electromagnetic interference and ability to endure extreme heat. In the market, replacing copper sensors with fiber optic is one of the notable market trends. This shift is based on excellent capabilities in terms of speed of data transmission, resistance to extreme environments, and accuracy. However, high fiber optic costs are the challenge, restricting large-scale adoption in some sectors (BCC Research, 2024).

An optical fiber is a transparent, flexible, and cylindrical cable made of silica or plastic thicker than that of human hair (Figure 6a) (Senior and Jamro, 2009). Optical fiber guide light with low losses to long distances. Single-index optical fibers include a transparent core covered with lower refractive index. The total reflection guides light into the core as per waveguide analysis. The energy of light is not completely trapped in the core, but a part of light moves in the cladding. When the core-clad interface is hit by the incident at angles bigger than its needed angle, light is guided and reflected totally in the fiber.

At smaller angles, the incident light meeting the interface is refracted to the cladding. The least angle is the critical one which was needed for achieving the total internal reflection, defined by refractive index change among the cladding and core materials (Arie et al, 1986).

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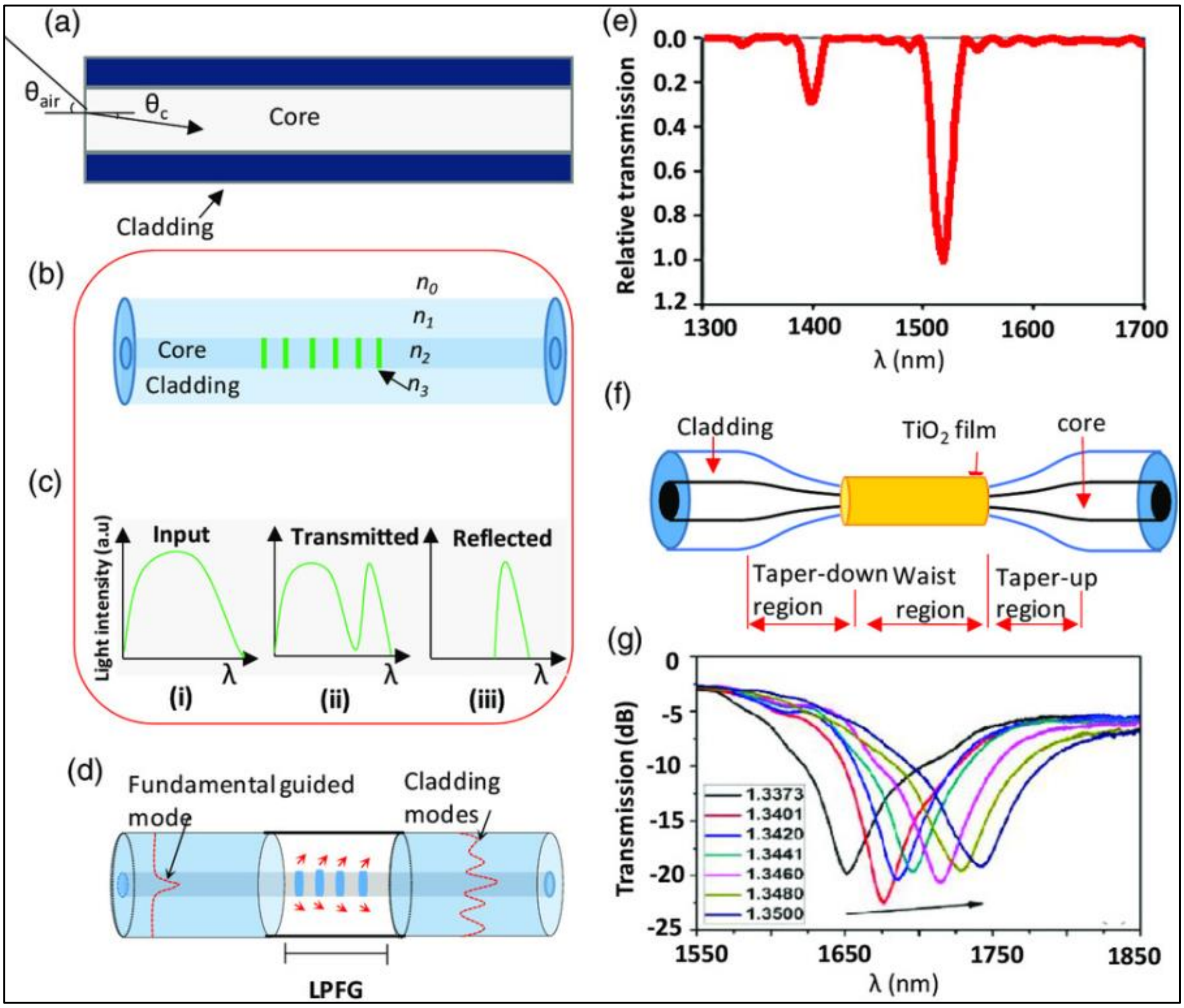

Fig 6 Types of Optical Fibres
Source: Elsherif et al (2022)

There are basically seven types of optical fibers (Figure 6) - (a) illustrates a step-index optical fibre, (b) fiber Bragg gratings; (c) reflected and transferred ranges of light guided in "fibre Bragg grating" in comparison to input spectra; (d) long-period grating fibre; (e) transfer spectra of fibre grating over the longer period with loss dips; (f) tapered single-mode fibre where analyte-responsive layer covers the tapered segment; (g) transmission range for tapered optical fibre Source - Bundalo et al (2017)

There are two types of fibers on the basis of several guided modes – multimode and single-mode fibers. The core diameter of single-mode fiber is 8-10 µm to work in a short infrared area. On the other hand, core diameter of multimode fibers is ranging from 50 to 100 µm and they are used to transfer high power (Davis, 1985). In optical fiber, the "numerical aperture (NA)" defines several angles over which fibre can guide, receive, and release light signals. In the step-index fibre, the NA is given by the change in refractive index among the cladding and core materials (Eq. 1).

$$\mathrm{NA} = \sqrt{n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2} = n_{\mathrm{air}} \sin\theta_{\mathrm{air}} \quad (1)$$

Here "n_{co}, n_{cl} , and θ_{air} are the deflective indices of the core, cladding and incident angle of light rays, respectively. The measure reflective of "angle, θ_{air} is determined relative to axis of core" (Figure 6a) (Bundalo et al, 2017). The range of incident angles is accepted by the NA for light leaving or passing through the fiber. Data is provided about several optical modes by a "normalized frequency (V)" to propagate modes in the fiber relying on the NA along with core diameter. Eq (2) defines the normalized frequency.

$$V = (\mathrm{NA})\,\frac{2\pi a}{\lambda} \quad (2)$$

Here, a is the fiber core radius and λ is the wavelength in free space (Bundalo et al, 2017). When it comes to develop chemical and bio-chemical sensors, the rapid growth has improved food, water quality tracking, healthcare systems, and helped the industry to produce standard products. Electronic sensors rule the sensor market and they face signal change, and are vulnerable to electromagnetic interference, along with meeting constant calibration (Riza et al, 2020). Apart from the need for remote sensing/tracking, these

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limitations have directed the attention of researchers for using sensors based on optical fibers.

Using photon to transmit the signal rather than electron, optical fibers become immune to electromagnetic intrusions (Akay, 2006). There are several ways for optical fibers acting as analytical science. The fibers enable carrying out of optical microscopy over long distances to reach sites that cannot be accessed by traditional spectroscopy (Delaney and Harris, 2006). Additionally, less common methods are enabled by optical fibers related to interrogation like "evanescent wave and spatially resolved spectroscopy" (Wang and Wolfbeis, 2019). Optical fibers are available to deliver signals with large range of spectral ranges for sensing applications as background noise is weak and lasers used are cheap as light sources (Wang and Wolfbeis, 2019).

Optical fibers play a major sensing role in various fields, especially in the fields of biomedicals, because of their benefits like flexibility, compactness, chemical inertness, biocompatibility, and feasibility to be functionalized and machined (Carvalho et al, 2021). Optical-fiber sensors are enabled with the rise in photonics and optics, biology, and chemistry in different areas, such as, medicine, oil and gas industry, food production, and environment monitoring. They become suitable to integrate with needles and catheters with optical fibers, which are used widely for point-of-care diagnostics and in-vivo sensing (Vaiano et al, 2016).

They are ideal to examine small sample sizes and limited remote areas for their fine dimensions (Carvalho et al, 2021). In addition, they are strong for extreme environments like high humidity, toxic environments, and high temperature with high amount of explosive and corrosive gases (like oil rigs, nuclear power plants, and gas/oil pipeline) because of their robust mechanical and material properties. Optical fiber sensors can measure over one parameter simultaneously and independently (Carvalho et al, 2021).

Integrating functioning structures and materials in optical fiber has been widely performed for specific sensing over the past decades. However, there are various limitations in applicability because of modest preparedness and control to integration approaches. Challenges for developing platforms related to optical fiber technology can compete with more mature approaches (Vaiano et al, 2016). Hence, intensive studies are needed for adjusting the fabrication to operate on optical fibers. With microelectronic industry, a lot of existing nano/microfabrication approaches have been designed to work on planer substrates. They are not simple for optical fibers due to small curved surfaces and cross-section of fibers (Vaiano et al, 2016). Intensive research has been conducted on developing major routes enabling overall control at nanoscales. For depositing and pattering materials, self-organization approaches and nanotechnologies have been developed and applied to optical fiber platforms.

III. MODULATION WITH MZM

With frequencies of around 200THz, the electromagnetic waves in optical fibers can transfer data. To convey the signal, multiple parameters can be modulated in electromagnetic wave. In a lot of traditional communication systems, modulation can be made possible by varying amplitude of optical wave. However, the phase of the carrier and amplitude enables improved use of complex plane, where data systems yield enhanced spectral efficiency. While EAMs work on the principle of absorption, Mach-Zehnder modulator (MZM) works on interference, managed by modulating optical stage (Kaminow and Willner, 2008). The 90-degree phase shift between cross-coupling and direct-pass outputs enables phrase diversity and adopt MZMs with optical hybrids at 90º. Figure 7 illustrates the linkage between input and output optical fields.

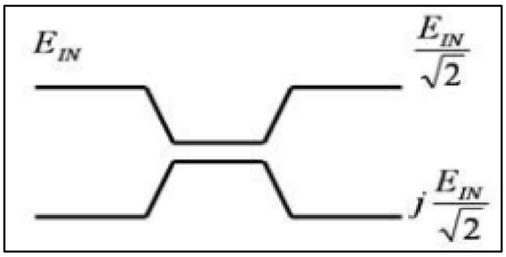

Fig 7 Transfer of Optical Fibre Coupler
Source: Makovejs (2011)

For MZM, two couplers of optical fibre are placed into the interferometric arrangement with shifters of voltage-managed phase (Figure 8).

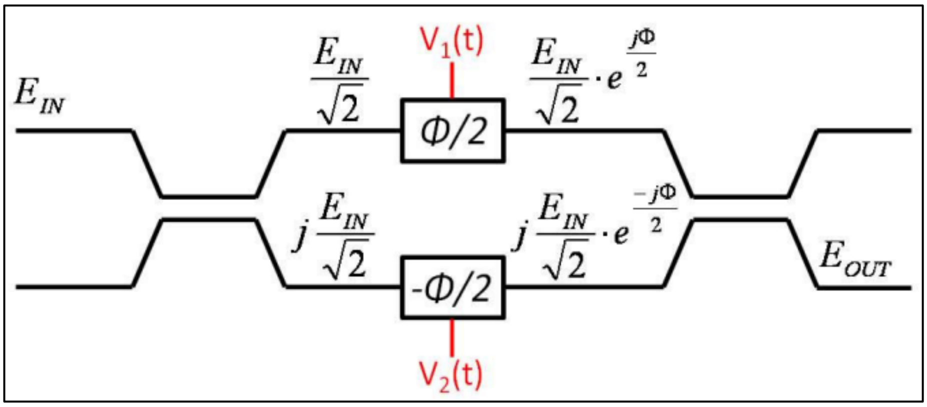

Fig 8 Linkages between Optical Fibres in MZM
Source: Makovejs (2011)

Adding optical fields spread through total optical output field is illustrated in Eq (3).

$$E_{OUT} = \frac{1}{\sqrt{2}} j \frac{E_{IN}}{\sqrt{2}} e^{\frac{j\Phi}{2}} + \frac{j}{\sqrt{2}} \frac{E_{IN}}{\sqrt{2}} e^{\frac{-j\Phi}{2}} =$$
$$= \frac{jE_{IN}}{2}\left(e^{\frac{j\Phi}{2}} + e^{\frac{-j\Phi}{2}}\right) = E_{IN} j\cos\left(\frac{\Phi}{2}\right) \quad (3)$$

It means the ratio of optical fields "output vs. input" and field transfer function is suggested by periodic function (Figure 9a). The function of amplitude transfer is square of modulus of function of field transfer $\left|\frac{E_{OUT}}{E_{IN}}\right|^2$ (Figure 9b). Both phase and amplitude of signal may be modulated, as per driving conditions. Another major application is generating RZ pulses in a MZM, where it is based on a sinewave.

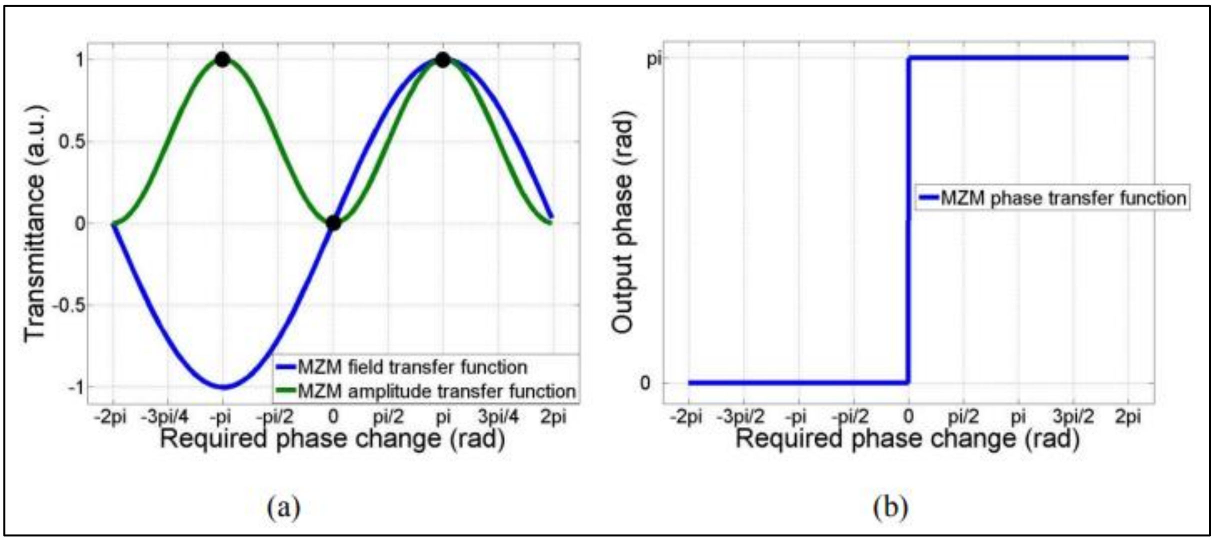

Fig 9 Functions of MZM Transfer – (a) Amplitude and Field of MZM (b) Phase of MZM
Source: Makovejs (2011)

It is possible to transform the phase modulation into amplitude function when interference is used among two arms. Those modulators are useful in push-pull (2-voltage sources) and single-sided function. The benefit is smaller for push-pull MZM to drive voltage needed and reduce footprint because of smaller MZM size.

IV. RESULTS AND DISCUSSION

Fibre optic sensors are very important in different applications and industries because of their different potential and benefits. They can measure and detect slight changes in pressure, temperature, vibration, strain, and chemical composition. They are highly sensitive to detect subtle changes which may be important in several uses. These sensors are highly valuable for remote sensing over long range. Unlike conventional electrical sensors, fibre optic can transmit data thousands of kilometers without degrading quality. This way, they become ideal for uses in challenging or hazardous areas.

Fibre optic sensors connect various sensors to an individual fibre optic cable. It monitors various parameters at the same time to reduce cost and complexity in installation. These sensors are light and small, making them ideal for uses where weight and space limitations are high, including automobiles, aircraft, and medical equipment. Optical fibre has been found to be most efficient in high-speed transmission of data with low degradation, excellent bandwidth, and uninterrupted supply of communication over long distances. This study suggests that traditional WDM technique has specific spectral range. Hence, OTDM emerges as a promising approach to deliver high-speed communication.

At 80 Gbit/s, the proposed system suggests accurate multiplexing in delay range, short optical pulses, and modulators for smooth multiplexing without any degradation of quality. Findings of the study further suggest that modern modulation and coherent detection approaches deliver excellent performance in comparison to traditional transmission systems. Apart from telecom systems, findings of the study highlight the applications of optical fiber like health monitoring, biomedical networks, automation, smart manufacturing, and monitoring. Overall, with these developments, it can be suggested that future communication and optical network technologies will constantly integrate high-capacity connections with smart sensing, making optical fibre ideal for Industry 4.0 and future networks.

V. CONCLUSION

This study was conducted on experimental design of optical fibre transmission systems with higher bitrate and longer reach. The "optical time-division multiplexing (OTDM)" was used with bitwise phase control and spectrally-efficient formats were used with coherent detection.

It is concluded that the OTDM channels can enhance the distance of maximum transmission by around 70%, even with optimization of bit-wise phase difference and overall use may not offer practical benefit in terms of product of capacity

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distance. It is when tolerance to "polarization-mode dispersion (PMD)" and "chromatic dispersion (CD)" is reduced. Using advanced modulation is a better way to enhance the bitrate and provide benefits in terms of "spectral efficiency (SE)".

Overall, it is concluded that using coherent detection at 100Gbit/s is the configuration needed to reach transatlantic transmission. In the bitrate per carrier, further rise can sill be needed with more complex formats to achieve enhanced spectral efficiencies.

REFERENCES

[1]. Akay, M. (2006). *Wiley encyclopedia of biomedical engineering*. Wiley, Hoboken, NJ, USA 2006.

[2]. Arie, A., Karoubi, R., Gur, Y. S., & Tur, M. (1986). Measurement and analysis of light transmission through a modified cladding optical fiber with applications to sensors. *Applied optics*, *25*(11), 1754-1758.

[3]. Arroyo, E., Tentori, D., Garcia, A., Valdez, R., Armenta, M. A., Nava, O. J., ... & Olivas, A. (2023). Carbon Quantum Dot Optical Properties for potential infiltration into Hollow Core Photonic Crystal Fibers. *Particle & Particle Systems Characterization*, *40*(6), 2200200.

[4]. BCC Research (2024). Fiber optic sensors market size and industry analysis, 2024-2029. https://www.bccresearch.com/market-research/photonics/fiber-optic-sensors-markets-report.html

[5]. Boerner, C., Schubert, C., Schmidt, C., Hilliger, E., Marembert, V., Berger, J., ... & Schmauss, B. (2003, March). 160 Gbit/s clock recovery with electro-optical PLL using a bidirectionally operated electroabsorption modulator as phase comparator. In *Optical Fiber Communication Conference* (p. FF3). Optica Publishing Group.

[6]. Boivin, L., & Chraplyvy, A. R. (2000, March). Testing optical time-division multiplexed transmission systems with interleaved bit sequences. In *Optical Fiber Communication Conference* (p. WM35). Optica Publishing Group.

[7]. Bundalo, I. L., Nielsen, K., Woyessa, G., & Bang, O. (2017). Long-term strain response of polymer optical fiber FBG sensors. *Optical Materials Express*, *7*(3), 967-976.

[8]. Butt, M. A., Kazanskiy, N. L., Khonina, S. N., Voronkov, G. S., Grakhova, E. P., & Kutluyarov, R. V. (2023). A review on photonic sensing technologies: status and outlook. *Biosensors*, *13*(5), 568.

[9]. Butt, M. A., Kazanskiy, N. L., Khonina, S. N., Voronkov, G. S., Grakhova, E. P., & Kutluyarov, R. V. (2023). A review on photonic sensing technologies: status and outlook. *Biosensors*, *13*(5), 568.

[10]. Butt, M. A., Voronkov, G. S., Grakhova, E. P., Kutluyarov, R. V., Kazanskiy, N. L., & Khonina, S. N. (2022). Environmental monitoring: A comprehensive review on optical waveguide and fiber-based sensors. *Biosensors*, *12*(11), 1038.

[11]. Cai, J. X., Cai, Y., Davidson, C. R., Lucero, A., Zhang, H., Foursa, D. G., ... & Bergano, N. S. (2011, March). 20 Tbit/s capacity transmission over 6,860 km. In *Optical Fiber Communication Conference* (p. PDPB4). Optica Publishing Group.

[12]. Cai, J. X., Cai, Y., Sun, Y., Davidson, C. R., Foursa, D. G., Lucero, A., ... & Bergano, N. S. (2010, September). 112× 112 Gb/s transmission over 9,360 km with channel spacing set to the baud rate (360% spectral efficiency). In *36th European Conference and Exhibition on Optical Communication* (pp. 1-3). IEEE.

[13]. Cai, J., Liu, Y., & Shu, X. (2023). Long-period fiber grating sensors for chemical and biomedical applications. *Sensors*, *23*(1), 542.

[14]. Carvalho, I. A., Silva, N. A., Rosa, C. C., Coelho, L. C., & Jorge, P. A. (2021). Particle classification through the analysis of the forward scattered signal in optical tweezers. *Sensors*, *21*(18), 6181.

[15]. Chen, M. Q., He, T. Y., Zhao, Y., & Yang, G. (2023). Ultra-short phase-shifted fiber Bragg grating in a microprobe for refractive index sensor with temperature compensation. *Optics & Laser Technology*, *157*, 108672.

[16]. Cruz, J., & Fangueiro, R. (2016). Surface modification of natural fibers: a review. *Procedia Engineering*, *155*, 285-288.

[17]. Davis, C. M. (1985). Fiber optic sensors: an overview. *Optical engineering*, *24*(2), 347-351.

[18]. Delaney, P., & Harris, M. (2006). Handbook of biological confocal microscopy.

[19]. Divya, J., & Selvendran, S. (2023). Surface plasmon resonance-based gold-coated hollow-core negative curvature optical fiber sensor. *Biosensors*, *13*(2), 148.

[20]. Du, C., Wang, Q., Zhao, S., & Deng, X. (2023). Biological sensors based on long period fiber grating. *Optics & Laser Technology*, *158*, 108936.

[21]. Elsherif, M., Salih, A. E., Muñoz, M. G., Alam, F., AlQattan, B., Antonysamy, D. S., ... & Butt, H. (2022). Optical fiber sensors: Working principle, applications, and limitations. *Advanced Photonics Research*, *3*(11), 2100371.

[22]. Ghassemlooy, Z., Uysal, M., Khalighi, M. A., Ribeiro, V., Moll, F., Zvanovec, S., & Belmonte, A. (2016). An overview of optical wireless communications. *Optical Wireless Communications: An Emerging Technology*, 1-23.

[23]. Gupta, B. D., & Kant, R. (2018). Recent advances in surface plasmon resonance based fiber optic chemical and biosensors utilizing bulk and nanostructures. *Optics & Laser Technology*, *101*, 144-161.

[24]. Haider, F., Ahmmed Aoni, R., Ahmed, R., Amouzad Mahdiraji, G., Fahmi Azman, M., & Adikan, F. R. M. (2020). Mode-multiplex plasmonic sensor for multi-analyte detection. *Optics Letters*, *45*(14), 3945-3948.

[25]. Hasegawa, A. (2004). Theory of information transfer in optical fibers: A tutorial review. *Optical Fiber Technology*, *10*(2), 150-170.

[26]. Hengoju, S., Shvydkiv, O., Tovar, M., Roth, M., & Rosenbaum, M. A. (2022). Advantages of optical fibers for facile and enhanced detection in droplet

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug188

microfluidics. *Biosensors and Bioelectronics*, *200*, 113910.

[27]. Jepsen, K. S., Poulsen, H. N., Clausen, A. T., Buxens, A., & Stubkjaer, K. E. (1998, September). Investigation of cascadability of add-drop multiplexers in otdm systems. In *24th European Conference on Optical Communication. ECOC'98 (IEEE Cat. No. 98TH8398)* (Vol. 1, pp. 619-620). IEEE.

[28]. Jiao, L., Zhong, N., Zhao, X., Ma, S., Fu, X., & Dong, D. (2020). Recent advances in fiber-optic evanescent wave sensors for monitoring organic and inorganic pollutants in water. *TrAC Trends in Analytical Chemistry*, *127*, 115892.

[29]. Johari, S. H., Cheak, T. Z., Rahim, H. R. A., Jali, M. H., Yusof, H. H. M., Johari, M. A. M., & Harun, S. W. (2022). Formaldehyde sensing using tapered U-shape plastic optical fiber coated with zinc oxide nanorods. *IEEE Access*, *10*, 91445-91451.

[30]. Kagawa, M., Murai, H., Tsuji, H., Sasaki, K., & Fujii, K. (2008). Control and Stabilization of bit-wise phase correlation in 160 (4× 40) Gbit/s OTDM signal and its impact on transmission. *Optics Express*, *16*(14), 10039-10052.

[31]. Kamatani, O., & Kawanishi, S. (1996). Prescaled timing extraction from 400 Gb/s optical signal using a phase lock loop based on four-wave-mixing in a laser diode amplifier. *IEEE Photonics Technology Letters*, *8*(8), 1094-1096.

[32]. Kaminow, I. P., Li, T., & Willner, A. E. (2008). *Optical Fiber Telecommunications V. Volume B, Systems and Networks*. Elsevier Science Limited.

[33]. Kazanskiy, N. L., Khonina, S. N., & Butt, M. A. (2022). Recent development in metasurfaces: a focus on sensing applications. *Nanomaterials*, *13*(1), 118.

[34]. Khonina, S. N., Kazanskiy, N. L., Butt, M. A., & Karpeev, S. V. (2022). Optical multiplexing techniques and their marriage for on-chip and optical fiber communication: a review. *Opto-Electronic Advances*, *5*(8), 210127-1.

[35]. Kiroriwal, M., & Singal, P. (2024). Applications of photonic crystal fibers in optical communication. *Journal of Optical Communications*, *45*(4), 741-750.

[36]. Kroh, M., Ferber, S., Schmidt-Langhorst, C., Marembert, V., Schubert, C., Ludwig, R., & Weber, H. G. (2006, March). Transmitter enabling ultra-high speed transmission of phase modulated data signals up to 640 Gbit/s. In *Optical Fiber Communication Conference* (p. OWW1). Optica Publishing Group.

[37]. Lee, B. H., Min, E. J., & Kim, Y. H. (2013). Fiber-based optical coherence tomography for biomedical imaging, sensing, and precision measurements. *Optical Fiber Technology*, *19*(6), 729-740.

[38]. Li, B., Zhang, R., Bi, R., & Olivo, M. (2022). Applications of optical fiber in label-free biosensors and bioimaging: a review. *Biosensors*, *13*(1), 64.

[39]. Li, H., Ni, J., Zhao, Q., & Jiang, L. (2023). Surface modified optical fiber Fabry–Perot cavity pressure sensor with carbon film. *IEEE Sensors Journal*, *23*(9), 9353-9358.

[40]. Li, L., Zhang, Y. N., Zheng, W., Li, X., & Zhao, Y. (2022). Optical fiber SPR biosensor based on gold nanoparticle amplification for DNA hybridization detection. *Talanta*, *247*, 123599.

[41]. Liang, C., Bai, Q., Yan, M., Wang, Y., Zhang, H., & Jin, B. (2021). A comprehensive study of optical frequency domain reflectometry. *IEEE Access*, *9*, 41647-41668.

[42]. Liang, Y., Wei, X., Chu, S., Zhang, X., Fang, Y., & Peng, W. (2023). Tamm-surface plasmon resonances from nanograting-coupled plasmonic-photonic multilayer structure for an integrated fiber-optic sensing application. *Journal of Physics D: Applied Physics*, *56*(38), 385101.

[43]. Liu, C., Wang, J., Wang, F., Su, W., Yang, L., Lv, J., ... & Chu, P. K. (2020). Surface plasmon resonance (SPR) infrared sensor based on D-shape photonic crystal fibers with ITO coatings. *Optics Communications*, *464*, 125496.

[44]. Lyu, S., Wu, Z., Shi, X., & Wu, Q. (2022, December). Optical fiber biosensors for protein detection: a review. In *Photonics* (Vol. 9, No. 12, p. 987). MDPI.

[45]. Makovejs, S. (2011). *High-speed optical fibre transmission using advanced modulation formats* (Doctoral dissertation, UCL (University College London)).

[46]. Market Research Future. (2025). India fiber optic sensor market size, share & forecast 2035. https://www.marketresearchfuture.com/reports/india-fiber-optic-sensor-market-46115

[47]. Mermelstein, M. D. (1986). All-fiber polarimetric sensor. *Applied optics*, *25*(8), 1256-1258.

[48]. Meunier, D., Schruyers, J., Palla, R. G., Mendoza, C., Calberg, C., Heinrichs, B., ... & Mahy, J. G. (2023). Controlled-chemical etching of the cladding in optical fibers for the design of analytical sensors. *Optical Fiber Technology*, *78*, 103328.

[49]. Mitra, P. P., & Stark, J. B. (2001). Nonlinear limits to the information capacity of optical fibre communications. *Nature*, *411*(6841), 1027-1030.

[50]. Molle, L., Seimetz, M., Gross, D. D., Freund, R., & Rohde, M. (2009, September). Polarization multiplexed 20 Gbaud square 16QAM long-haul transmission over 1120 km using EDFA amplification. In *2009 35th European Conference on Optical Communication* (pp. 1-2). IEEE.

[51]. Mortimore, D. B. (1988). Fiber loop reflectors. *Journal of lightwave technology*, *6*(7), 1217-1224.

[52]. Muanenda, Y., Oton, C. J., & Di Pasquale, F. (2019). Application of Raman and Brillouin scattering phenomena in distributed optical fiber sensing. *Frontiers in Physics*, *7*, 155.

[53]. Mulchandani, A., Pan, S., & Chen, W. (1999). Fiber-optic enzyme biosensor for direct determination of organophosphate nerve agents. *Biotechnology progress*, *15*(1), 130-134.

[54]. O'Keeffe, S., McCarthy, D., Woulfe, P., Grattan, M. W. D., Hounsell, A. R., Sporea, D., ... & Lewis, E. (2015). A review of recent advances in optical fibre sensors for

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug188

in vivo dosimetry during radiotherapy. *The British journal of radiology*, *88*(1050), 20140702.

[55]. Rahmani, B., Oguz, I., Tegin, U., Hsieh, J. L., Psaltis, D., & Moser, C. (2022). Learning to image and compute with multimode optical fibers. *Nanophotonics*, *11*(6), 1071-1082.

[56]. Rehman, S. U., Ullah, S., Chong, P. H. J., Yongchareon, S., & Komosny, D. (2019). Visible light communication: A system perspective—Overview and challenges. *Sensors*, *19*(5), 1153.

[57]. Ren, Z. H., Wang, Q., Zhao, W. M., Wang, L., Jiang, C. Q., Cong, X. W., ... & Zhang, K. K. (2022). A High-FOM surface plasmon resonance sensor based on MMF-TUMMF-MMF structure of optical fiber. *Optical Fiber Technology*, *72*, 102970.

[58]. Research and Markets. (2025). India Optical Fiber Cables Market, By Region, Competition, Forecast & Opportunities, 2021-2031F. https://www.researchandmarkets.com/report/india-optical-fiber-cable-market?srsltid=AfmBOopQPZIuASOUsIRUoZcsEOIHC19uOAfP1rG1Zzvcb2sKjQHwpGeo

[59]. Richter, T., Palushani, E., Schmidt-Langhorst, C., Nölle, M., Ludwig, R., Fischer, J. K., & Schubert, C. (2011, March). Single wavelength channel 10.2 Tb/s TDM-data capacity using 16-QAM and coherent detection. In *Optical Fiber Communication Conference* (p. PDPA9). Optica Publishing Group.

[60]. Riza, M. A., Go, Y. I., Harun, S. W., & Maier, R. R. (2020). FBG sensors for environmental and biochemical applications—A review. *IEEE sensors journal*, *20*(14), 7614-7627.

[61]. Savović, S., Simović, A., Drljača, B., Kovačević, M. S., Kuzmanović, L., Djordjevich, A., ... & Min, R. (2023). Power flow in multimode graded-index microstructured polymer optical fibers. *Polymers*, *15*(6), 1474.

[62]. Schilling, M., Blume, O., Nguyen, L. H., Schmidt, M., & Lach, E. (2002, November). OTDM planar lightwave components (PLCs) for multiplexing from 40 Gb/s to 80-640 Gb/s. In *The 15th Annual Meeting of the IEEE Lasers and Electro-Optics Society* (Vol. 2, pp. 887-888). IEEE.

[63]. Schubert, C., Berger, J., Diez, S., Ehrke, H. J., Ludwig, R., Feiste, U., ... & Petermann, K. (2002). Comparison of interferometric all-optical switches for demultiplexing applications in high-speed OTDM systems. *Journal of lightwave technology*, *20*(4), 618.

[64]. Senior, J. M., & Jamro, M. Y. (2009). *Optical fiber communications: principles and practice*. Pearson Education.

[65]. Shatalin, S. V., Treschikov, V. N., & Rogers, A. J. (1998). Interferometric optical time-domain reflectometry for distributed optical-fiber sensing. *Applied optics*, *37*(24), 5600-5604.

[66]. Shi, F., Zhang, H., Ye, Z., Tang, X., Qin, F., Yan, J., ... & Amano, H. (2022). Miniature optical fiber curvature sensor via integration with GaN optoelectronics. *Communications Engineering*, *1*(1), 47.

[67]. Shih, M., Nelson-Quillin, H. D., Garrett, K. E., Coyle, E. J., Secondo, R., Keyser, C. K., ... & Harper, E. S. (2023). Maximizing supercontinuum bandwidths in gas-filled hollow-core fibers using artificial neural networks. *Journal of Applied Physics*, *133*(23).

[68]. Singh, S., Chaudhary, B., Upadhyay, A., Sharma, D., Ayyanar, N., & Taya, S. A. (2023). A review on various sensing prospects of SPR based photonic crystal fibers. *Photonics and Nanostructures-Fundamentals and Applications*, *54*, 101119.

[69]. Smith, A. M. (1978). Polarization and magnetooptic properties of single-mode optical fiber. *Applied Optics*, *17*(1), 52-56.

[70]. Spammer, S. J., Swart, P. L., & Booysen, A. (1996). Interferometric distributed optical-fiber sensor. *Applied optics*, *35*(22), 4522-4525.

[71]. Theodosiou, A., & Kalli, K. (2020). Recent trends and advances of fibre Bragg grating sensors in CYTOP polymer optical fibres. *Optical Fiber Technology*, *54*, 102079.

[72]. Trebino, R., DeLong, K. W., Fittinghoff, D. N., Sweetser, J. N., Krumbügel, M. A., Richman, B. A., & Kane, D. J. (1997). Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating. *Review of Scientific Instruments*, *68*(9), 3277-3295.

[73]. Turkiewicz, J. P., Tangdiongga, E., Lehmann, G., Rohde, H., Schairer, W., Zhou, Y. R., ... & Waardt, H. D. (2005). 160 Gb/s OTDM networking using deployed fiber. *Journal of Lightwave Technology*, *23*(1), 225.

[74]. Vaiano, P., Carotenuto, B., Pisco, M., Ricciardi, A., Quero, G., Consales, M., ... & Cusano, A. (2016). Lab on Fiber Technology for biological sensing applications. *Laser & Photonics Reviews*, *10*(6), 922-961.

[75]. Verdurmen, E. J. M., Zhao, Y., Khoe, G. D., & de Waardt, H. (2004). OTDM demultiplexing using HNLF in a NOLM at 160 Gb/s. In *Proceedings of Lasers and Electro-Optics Society Conference*.

[76]. Wang, X. D., & Wolfbeis, O. S. (2019). Fiber-optic chemical sensors and biosensors (2015–2019). *Analytical chemistry*, *92*(1), 397-430.

[77]. Wang, Z., Zhang, W., Liu, X., Li, M., Lang, X., Singh, R., ... & Kumar, S. (2022). Novel optical fiber-based structures for plasmonics sensors. *Biosensors*, *12*(11), 1016.

[78]. Weber, H. G., & Nakazawa, M. (2007). Introduction to ultra-high-speed optical transmission technology. In *Ultrahigh-Speed Optical Transmission Technology* (pp. 1-20). Berlin, Heidelberg: Springer Berlin Heidelberg.

[79]. Weber, H. G., Ferber, S., Kroh, M., Schmidt-Langhorst, C., Ludwig, R., Marembert, V., ... & Schubert, C. (2005, September). Single channel 1.28 Tbit/s and 2.56 Tbit/s DQPSK transmission. In *31st European Conference on Optical Communications (ECOC 2005)* (pp. v6-3). Stevenage UK: IEE.

[80]. Xie, Y., Wang, M., Zhong, Y., Deng, L., & Zhang, J. (2023). Label-free anomaly detection using distributed optical fiber acoustic sensing. *Sensors*, *23*(8), 4094.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26aug188

[81]. Yin, Z., Jing, X., Bai, G., Wu, B., Gao, Z., Liu, C., ... & Li, Y. (2023). Experimental study of dual-parameter SPR sensor with integrated sensing channel. *IEEE sensors journal*, *23*(8), 8385-8390.
[82]. Zhang, H., Zhou, X., Li, X., Gong, P., Zhang, Y., & Zhao, Y. (2023). Recent advancements of LSPR fiber-optic biosensing: Combination methods, structure, and prospects. *Biosensors*, *13*(3), 405.
[83]. Zhang, J., Mai, X., Hong, X., Chen, Y., & Li, X. (2022). Optical fiber SPR biosensor with a solid-phase enzymatic reaction device for glucose detection. *Sensors and Actuators B: Chemical*, *366*, 131984.
[84]. Zhou, X., & Yu, J. (2009, September). 200-Gb/s PDM-16QAM generation using a new synthesizing method. In *2009 35th European Conference on Optical Communication* (pp. 1-2). IEEE
[85]. Zhu, C., Gerald, R. E., & Huang, J. (2021). Micromachined Optical Fiber Sensors for Biomedical Applications. In *Biomedical Engineering Technologies: Volume 1* (pp. 367-414). New York, NY: Springer US.