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EFFECTS OF FIBER NONLINEARITIES ON OPTICAL COMMUNICATION

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ABSTRACT
This paper focuses on the recent research in optical communications and the effects of fiber non linearities in optical communication. Moreover, this paper covers the investigation on characteristics of optical fiber, modelling/analysis of fiber nonlinearities and laser effect on optical fiber in the literature. This paper also provides the information about the parameters, methodology and materials used in optical fiber. Here, most commonly used material is fiber laser and its advantages are increased output power, peak power and optical quality. This paper further describes several types of nonlinearity effects on the basis of various methodologies such as dual parallel Mach–Zehnder modulator (DP-MZM), fiber optical parametric amplifiers (FOPA), Darboux transformation (DT) and scalar finite element method (SC-FEM) and many parameters are also discussed. Their applications are also discussed and relative study of these effects is presented. The primary purpose of this paper is to understand the effects of nonlinearities, and to encourage further research in this area.

KEYWORDS: Fiber; optical; modelling; analysis; nonlinearity.

INTRODUCTION
Optical fiber communication means transmitting information from one place to another by sending pulses of light. Moreover, optical fiber communication system has practised spectacular evolution over the past two decades [20]. Generally, fiber is a natural or synthetic substance that is significantly longer, wider and the fibers are often used in the manufacturing of other materials. Generally, two basic light sources are used for fiber optics like light emitting diodes and laser diodes [4]. Generally, Optical fiber is used by many telecommunications companies to transmit telephone signals and cable television signals. Moreover, optical fiber has many advantages over existing copper wire in long-distance, high-demand applications. However, infrastructure development within cities was relatively difficult and time-consuming, and fiber-optic systems were complex and expensive to install and operate. Due to these difficulties, fiber-optic communication systems have primarily been installed in long-distance applications. Moreover, Optical fibers consists of a core, guiding light, cladding and also optical fibers are used in many different applications like telecommunication, data transfer and wastewater disinfection [3]. The optical fibers are polymethyl methacrylate and its mean diameter is 480µm and its thickness is 10µm. Hence, flexible or rigid illuminated surfaces can be produced and this technology typically used in many applications such as lighting, communication and pollution control in air environment [11]. However, numerous significant steps can involve during the optical fiber fabrication process and the modelling is an important method to develop the optical fibers. Here, optical waveguide modelling method can be considered as two methods such as analytical and numerical method. Numerical method uses numerous approaches like scalar or vectorial finite difference method and beam propagation method [12]. In general, optical fibers can act as a sensing element for various external parameters. Meanwhile, optical fiber sensors have many advantages like immunity to electromagnetic interference, small size, high sensitivity, and it is easy for implementing multiplexed or distributed sensors. Now-a-days, numerous fiber based displacement sensors have demonstrated. For instance, a compact micro displacement sensor based on air cavity sensor and displacement sensor also premeditated by placing a mirror in front of the multimode fiber [15]. However, several sensing application occurs linear birefringence is induced because of fiber bends. Similarly, in commercial fiber there is vaguely unavoided birefringence occurs from a number of extrinsic or intrinsic factor [14]. Generally, lasers are typically used in laser processing thus the fiber laser technologies expands the wavelength region in-between the mid infrared and visible [6]. Additionally, high power fiber laser system is an important technology it collects more excitation LD outputs. Here, fiber laser power is restricted by nonlinear optical effect. Also, another one important technology is double clad fiber and it is

composed of two claddings [5]. Moreover, dual frequency laser (DFL) is a better option to external modulation for microwave signal in the radar system and optoelectronic microwave oscillators. However, DFL is diode pumped solid state laser here the anisotropic element within the cavity permit lifting polarised eigen states [9]. Therefore, to assure the demand for capacity, here focus on increasing spectral efficiency by reducing the guard interval in wavelength division multiplexing. Generally, an optical fiber light is detained to a small transverse region so even moderate optical powers lead to high optical intensities [15]. For intense electromagnetic fields, any dielectric medium behaves like a nonlinear medium. Moreover, light often propagates over considerable distances in a fiber. Hence, nonlinear effects due to fiber nonlinearities often have massive effects. However, nonlinearity effects in optical communication occur due to change in the intensity dependence of refractive index or due to inelastic-scattering. Here, the intensity for the scattered light grows exponentially while incident power exceeds a certain threshold value [13]. Generally, Salinity plays a vital role in chemical, manufacturing process control and protection of ecosystems. Now-a-days, measurement of salinity by means of optical fiber technology has engrossed lots of attentions. Moreover, several fiber optic salinity sensors have been reported that is done on the basis of fiber Bragg gratings (FBGs) long-period fiber gratings (LPGs), and various optical fiber interferometers. However, fabrication process of optical fiber gratings is quite complex. Optical fiber interferometers can measure salinity from the phase-related spectral shift with high sensitivity, but the reading accurateness is typically poor due to the broad bandwidth of their interference patterns [20] [21]. Generally, optical wireless communication is protocol independent, secure and it is used to meets the requirements for the future communication technologies [17] [18]. However, the performance of optical systems with high capability targets could be demand in cost sensitive situation. Hence, DMT (Discrete Multi tone) modulation is used and here the optical channel is highly frequency is restricted because of inexpensive devices [32] [19]. Optical microfiber, due to its different propagation properties, provides versatile waveguide structures to fabrication for several compact photonic devices. Moreover, the nonlinear coefficient of the microfiber is greater than that the standard optical fiber. Hence, the microfiber can be regard as highly non linear optical waveguide for many applications in the field of nonlinear optics. However, different nonlinear optical response for grapheme and it act as an outstanding nonlinear optical. Hence, by combining the large nonlinear coefficient of microfiber, it is expected that the graphene-decorated microfiber can act as a high-performance photonic device which simultaneously provide dual functions of high nonlinearity and saturable absorption [22]. Moreover, compact fiber laser operating in the 1.2μm region is used in many applications such as molecular spectroscopy, biomedical diagnostics, laser guide star adaptive optics and oxygen atmospheric sensing etc [23]. Generally, the basic design for multi-wavelength lasers contains a broadband active medium to offer the gain profile and a filter for wavelength selection. Typically, the multi-wavelength laser stability depends on the gain medium. Here, the better options to contribute the output power stability for the multi-wavelength fiber lasers are the inhomogeneous mediums [24]. Generally, Ultrafast mode locked fiber lasers acquires widespread applications in nonlinear optics, material processing, medicine and sensing. A passively mode-locking technique with saturable absorber is the efficient technique for generating optical pulse from picoseconds to femtosecond regime. Here, new and high-performance of saturable absorber are always attracted security for ultrafast photonics [25]. Some of the recent research works regarding the fiber optical communication are discussed in below section.

MATERIALS AND METHODS FOR OPTICAL FIBER CHARACTERIZATION

Characteristics of optical fiber

In 2016, EmmaM.Carland et al [1] have presented optical fibers on the basis of cochlear electrode arrays. Here, embedding an optical fiber in electrode array can change its stiffness properties and it might also affect the level of trauma while insertion. Hence, they proposed acoustic sensors to minimise insertion trauma and also it helps in delivery of light in optical nerve stimulation. The experimental outcomes have proved that the optical fibers with a diameter of 50μm could be embedded in electrode array without changing the stiffness properties of the array. Moreover, they proposed conventional cochlear electrode arrays with a number of custom arrays used in animal trials.

In 2016, Pavol Stajanca et al [2] have presented gamma radiation effects on a low-loss per fluorinated polymer optical fiber (PF-POF) on the basis of Cytop polymer. Here, Radiation Induced Attenuation (RIA) is used to measures the fiber accumulated dose. Moreover, spectral characteristic of RIA in the VIS-NIR spectral region was calculated. Generally, interaction of ionizing radiation with polymer material of the fiber does not lead only to direct deterioration of the fiber transmission but influences also its climatic sensitivity and stability. Finally, simulation results have confirmed that the RIA in the UVeVIS spectral region comes partly from the absorption on free radicals and partly from the absorption on new compounds.

In 2016, S.E. Lam et al [7] addressed the issue in TTP (Time Temperature Profile) parameters with special attention to the determination of the kinetic parameters for the glow curve. Here, Germanium (Ge) doped silica optical fibers have developed as a thermo-luminescent (TL) dosimeter and also it can be used in several applications. Generally, doped silica optical fibers develop the tailor made doped silica optical fibers with specific TL dosimetry applications. Finally, results have confirmed that the potential relationship between the TTP parameters and the kinetic parameters of TL glow curves for the tailored made Ge-doped silica optical fibers.

In 2016, Chloe et al [11] addressed the issue in optical ageing phenomenon of optical fiber fabrics in presence of TiO2 coating. Hence, they focused on UVA optical ageing of polymethyl methacrylate (PMMA) optical fiber fabrics coating with TiO2. Moreover, major advantage of PMMA method is inexpensive, high ductility, a big core diameter, and it also shows easy handling characteristics. However, major problem in PMMA is the photochemical degradation of PMMA optical fibers in presence of UV radiation. Finally, the results show that the mathematical model of optical fiber fabrics and it is based on a constant hole density profile.

Modelling /analysis on fiber nonlinearities

In 2014, Arash Bahrami et al [3] have proposed optical microwave radio over fiber system and integrated dual parallel Mach Zehnder modulator (DP-MZM) is biased at the maximum transmission biasing point. Here, two modulation schemes are identified, namely binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) over fiber spans of standard single mode fiber. Finally, experimental result shows that the second-order sideband of MW has the potential to contribute error free transmission for BPSK and QPSK.

In 2013, H. Pakarzadeh et al [8] introduced the noise properties of both one-pump (1-P) and two pump FOPA (fiber optical parametric amplifiers) and also different feature of FOPA for the noise suppression in gain saturated regime is developed. Moreover, noise suppression can be identified for several specific powers at which the slope of the output signal power vs. the input one is zero Here, Pump, signal and idler are the interacting waves in a 1-PFOPA with the angular frequencies. Whereas, for 2-P FOPAs can simply consider four interacting waves propagating along the fiber known as pump1, pump2, signal and idler. However, 1-P FOPA have been only identified experimentally without any theoretical model and also in 2-P FOPA no theoretical and experimental work has been reported to examine the noise suppression.

In 2014, Li-Chen Zhao et al [10] focused on rogue waves in a nonlinear fiber with cubic and quintic nonlinearities, linear and nonlinear dispersion effects. Here, they identified the rogue wave with higher order effects have exact shape with the nonlinear equation.Moreover, they proposed exact rational solution for the KE model through Darboux transformation method and it indicates the RW can remain with proper higher-order effects and the quintic nonlinear terms and nonlinear dispersion effects just affect the velocity of RW on the retarded time. Meanwhile, the experimental results show that the dynamics of nonlinear localized waves and RW behaviour could exist in nonlinear systems.

In 2016, Sanjeev Kumar Raghuwanshi et al [12] focused on a modified finite element method (FEM) on the basis of variation formulation for the cylindrical coordinates system, which can be consider as complicated refractive index profile. Moreover, they have characterized the dispersion property of linearly chirp types of refractive index profile. Meanwhile, the accuracy of FEM has been tested with respect to the number of core division and finally it achieves the flat waveguide dispersion property over the band. Experiment results relieved that the numerical error becomes less than 2 % for the number of the core divisions in FEM analyses.

Laser effect on optical fiber

In 2013, C.L. Anyi et al [4] propose an approach based on the nanosecond erbium-doped fiber lasers (EDFL) on the basis of nonlinear polarisation rotation (NPR) effect. Moreover, Nanosecond EDFL has advantages of ultrafast fiber lasers for high pulse energy and average power scaling. Meanwhile, Nanosecond laser pulse can be obtained through an active or a passive method. Here, active method use electro-optic modulation or acousto-optic modulation approaches this is very costly and bulky. A passive method is done on the basis of either a Q-switching or mode-locking approach. Finally, the result shows that the ring EDFL starts to generate a stable multi-wavelength comb as the 980 nm pump power hits and the threshold at 87.6 mW.

In 2012, M. Murakami et al [5] focused on planar-core optical fiber and laser oscillation. Moreover, planar core fiber offers a good structure for high-power fiber lasers. It also has advantages such as no skew-ray propagation mode, less nonlinear effects due to larger core area, and easy line beam generation. Moreover, the planar-core

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optical fiber is a beneficial Structure for high-power laser processing devices. Here, planar core optical fiber shows a fabricated planar core fiber and a laser oscillation demonstration. The planar core configuration helps suppress the skew-ray mode and enlarge the fiber core area. Finally, line shape laser beam is necessary for an adequate annealing process on solar-cell wafers.

In 2015, Y. Fujimotoet al [6] investigated the novel design of a simple and compact tunable laser its tunability is 20 nm tunability between orange and red with a 130 µm and it is used in many applications. Here, tunable laser is laser source and it is achieved by using the chromatic aberration of a lens relay and a slit-like effect of the optical fiber core. Generally, Single mode Yb-doped fiber laser power reaches over 1 kW hence lasers are now extensively used in laser processing. Finally, the result shows ns-pulse generation WPFG fiber with graphene as a saturable absorber. Therefore, fiber laser technologies quickly expand the wavelength region between visible and mid-infrared.

In 2011, J. Maxin et al [9] have introduced dual frequency laser on the basis of an erbium-doped Distributed feedback fiber lasers Distributed feedback fiber lasers (DFB-FLs) for optical distribution of microwave signals. Generally, DFB-FLs are single mode, doped optical fibers in which a distributed Bragg grating is printed to create a cavity. Moreover, they presented Relative intensity noise (RIN) and the phase noise power spectral density of the beat note. Furthermore, structure ensures a single longitudinal mode emission with a narrow line width (6 kHz). However, a natural intrinsic birefringence or anisotropy owing to strains in the fiber core introduced by means of inscription of the periodic pattern with an intense ultraviolet source could be exploited for dual-frequency operation.

Table 1: Parameters used in characteristics of optical fiber

Parameters	**EmmaM.Carland et al [1]**	**Pavol Stajanca et al [2]**	**S.E. Lam et al [7]**	**Chloe et al [11]**
Deflection force (Nm)	✓			
Location of concentrated load (mm)	✓			
Embedded fiber (80µm)	✓			
Plain fiber (80 µm)	✓			
Buckling force (mN)	✓			
Length of fiber (mm)	✓			
Norm.rel.Intensity (db/m)		✓		
True stress (MPa)		✓		
Wavelength (nm)		✓		
RIA (db/m)		✓		
Radiation dose (kGy)		✓		
Annealing time (h)		✓		
Strain (%)		✓		
Wavelength (nm)		✓		
Normalized intensity (db)		✓		
HIA (db/m)		✓		
EPR signal (a.u)		✓		
B (mt)		✓		
EPR signal amplitude (a.u)		✓		
Raman shift (cm^{-1})		✓		
Time after irradiation (min)		✓	✓	
TL intensity (a.u.)			✓	
Heating Rate (cs^{-1})			✓	
Deconvoluted Tmax (k)			✓	
Peak temperature (c)			✓	
Peak integral (nc)			✓	
Ea (80) / Ea (50)			✓	
Distance x (mm)				✓
Emitted light intensity ($\mu W/mm^2$)				✓
Irradiance ($\mu W/mm^2$)				✓

Time of reaction (min)				✓
Concentration of formic acid (µmoVl)				✓
A (-)				✓
CCD counts	✓			

ANALYSIS ON FIBER NONLINEARITIES

Characteristics study

Table 1 shows the parameters that are used for characteristics of optical fiber in related works. Here, Emma M. Carland et al [1] states five parameters Deflection force (Nm), Location of concentrated load (mm), Plain fibre (80 µm), Embedded fibre (80µm), Buckling force (mN), Length of fibre (mm). Pavol Stajanca et al [2] used Wavelength (nm), RIA (db/m), Radiation dose (kGy), Annealing time (h), Norm. rel. Intensity (db/m), True stress (MPa), Strain (%), Wavelength (nm), Normalized intensity (db), HIA (db/m), EPR signal (a.u), B (mt), EPR signal amplitude (a.u), Time after irradiation (min), CCD counts, Raman shift (cm-1). S.E. Lam et al [7] worked on the parameters are Channel Intensity, Temperature, TL intensity (a.u.), Heating Rate (cs-1), Preheat temperature, Deconvoluted Tmax (k), Peak temperature (c), Peak integral(nc), Peak number, Ea (80)/Ea (50). Chloe et al [11] used parameters are Distance x (mm), Emitted light intensity (µW/mm2), Irradiance (µW/mm2), Time of reaction (min), Concentration of formic acid (µmoVl), A (-).

Table 2: Methodology used in modelling /analysis on fiber nonlinearities

Author	**Methodology**
Arash Bahrami et al [3]	(DP-MZM) dual parallel Mach–Zehnder modulator
H. Pakarzadeh et al [8]	fiber optical parametric amplifiers (FOPA)
Li-Chen Zhao et al [10]	Darboux transformation (DT)
Sanjeev Kumar Raghuwanshi et al [12]	scalar finite element method (SC-FEM)

Modelling and Analysis of fiber nonlinearities

Table 2 demonstrates that different methodology in Modelling/analysis on fiber nonlinearities. Here, Arash Bahrami et al [3] uses (DP-MZM) dual parallelMach–Zehnder modulator methodology and the advantage of this methodology is the low LO frequency which reduce the system cost. Moreover, DP-MZM operates at the maximum transmission biasing point (MTBP) which is the peak point of its biasing point to create optical double sideband suppressed carrier. H. Pakarzadeh et al [8] worked on fiber optical parametric amplifiers it is an important application in signal processing. The FOPA is used to remove the excess noise of noisy signals. Li-Chen Zhao et al [10] used Darboux transformation (DT) method it describes about the properties of the rational solution are similar to RW (Rogue wave). Moreover, it indicates that RW can subsist with proper higher order effects. Based on the analytical solution, it is suitable to study dynamics of RW with the cubic and quintic nonlinear terms. Sanjeev Kumar Raghuwanshi et al [12] worked on Scalar finite Element method (SC-FEM). Here, the dispersion graph, mode cut off condition, and group delay for highly complicated chirped type refractive index profile fiber are calculated. Moreover, convergence study of SC-FEM formulation is carried out with respect to the number of division in core and it is found that the numerical error occurs less than 2 % when the number of divisions in the core is more then 30.

Table 3: Materials used in Laser effect on optical fiber

Materials	C.L. Anyi et al [4]	M. Murakami et al [5]	Y. Fujimotoet al [6]	J. Maxin et al [9]
fiber lasers	✓		✓	✓
optical sensors	✓			
Pump	✓			
laser micromachining	✓			
optical fiber		✓		
Laser		✓		
solar-cell wafers		✓		
silica glass		✓		
infrared laser diodes		✓		
waterproof fluoride glass			✓	
absorber mirror			✓	
semiconductor saturable			✓	
gallium nitride-laser diode			✓	

polarisation controller				✓
Photodiode				✓
photo detector				✓

Laser Materials

Table 3 illustrates the different Materials used in laser effect on optical fiber. Here, C.L. Anyi et al [4], M. Murakami et al [5], Y. Fujimotoet al [6] and J. Maxin et al [9] use different materials in their research work. The fiber laser is a laser wherein the active gain medium is an optical fiber and this is associated to doped fiber amplifiers. Fiber optic sensor is a sensor that uses optical fiber also as the sensing element from a remote sensor. Optical fibers are used to transmit light between the two ends of the fiber and it is used to find practice in fiber-optic communications, where they allow transmission over longer distances and at higher bandwidths than the wire cables. Laser is a device which emits light during a process of optical amplification on the basis of stimulated emission of electromagnetic radiation. Polarization controllers can be operated without feedback, typically by manual adjustment or by the electrical signals from a generator, or with automatic feedback. A photo detector converts light signals that hit the junction into voltage or current. A photodiode is a semiconductor device that converts light into current.

CONCLUSION

In this paper, various characteristic features of the optical communication and its effects of fiber nonlinearities have been discussed. Here, effects of optical communication elaborate on the three main research areas: Characteristics of optical fiber, Modelling /analysis on fiber nonlinearities and Laser effect on optical fiber. In each section, we summarize our findings and provide additional details for research. Finally, the table illustrates the parameters, methodology and materials that are used in related works.

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