Thermal Dynamics in Optical Networks: Analyzing Spectral Bandwidth Reduction and Signal Distortion

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***Abstract*—The signal distribution of any fiber-optic network system is an important factor in optical communication, which determines the quality of the optical signal transmission. One of the important effects is the temperature degrees; that effect is on the main parameters of optical communication (of which the fiber optic is the main part). The main material in fiber optics is glass. And as is well known, temperature has a strong effect on the glass, especially the core of fiber optics, because the structure of fiber optics contains several glass layers with different refractive indexes. Hence, in the present article, the effect of temperature on the optical signal and other components of the optical network system has been analyzed and studied. The analysis includes aberration, dispersion, and distortion of the optical network communication signal. The result has been discussed and analyzed for variables in the BW of the spectral when the temperature changed.**

***Index Terms*—Aberration, Dispersion, Fiber-optic's networks, Optical signal transmission, Temperature effects.**

I. Introduction

The effect of temperature on the communications system is a clear and real fact due to the environmental condition of the optical system field (Ghassemlooy et al., 2019). The different temperature degrees have an important effect (The range between (heating) high temperatures and (freezing) low temperatures). It is very important to measure the effect of thermal on each part of the fiber-optic communication system: transmitter (light source), link (fiber optics), and receiver (photo detector), as shown in Fig. 1 (Winzer, 2014).

There are several sources of thermal effects; it depends on the components of the optical communication system. In other words, the effect of the thermal effect depends on many factors, such as the type of component materials, the duration of the thermal effect on the optical signal, and the way of the effect (direct or indirect) on the optical components (Yang et al., 2011).

In the present paper, the effect of a variable temperature degree on the optical signal (during analyzing the effect of thermal on the optical components) has been simulated and analyzed. The result factors (of optical signal) that have been analyzed are aberration and dispersion. Which also the result can show the quality of the optical signal and the reduction of it due to the thermal effect analyzed on the image plane. The seriousness of this research is to show the thermal effects on the optical signal of the fiber-optic communication network and to design a fiber-optic network with a minimum loss (as possible) in the optical signal.

This paper gives a better understanding of rising data transmission needs, the impact of temperature variations on data transmission, the advancements in network design, and the prediction of the modeling of fiber-optic networks. The present paper is structured into paragraphs. Paragraph two presents the related work about the thermal effect; Paragraph three presents the optical network structure; Paragraph four explains the main fiber optic and thermal effects; and Paragraph five shows the results and analysis. In the final sixth paragraph, the conclusion and future work of the paper were presented. Most previous researchers have studied the effect of thermal energy on the optical system or the general properties of the optical communication system. However, this article works on the properties of optical signals, such as bandwidth dispersion and intensity distribution at the image plane of the optical system.

II. Related Work

In recent years, many researchers have conducted a different type of simulation on the thermal effect on the fiber-optic signal. In Ref. (Fokoua et al., 2018), the author plains the reactivity of thermal delay of propagation and phase in fiber optics with a band of hollow-core photonic, where the results showed that the propagation delay is complete delay in sensitive to variation temperature degrees. In Ref. (Fokoua et al., 2019), the propagation delays thermal response and the hollow-core photonic band gap fiber phase accumulated through adequate fiber design with explanation, and the result shows the extraordinary prospects given by this exotic

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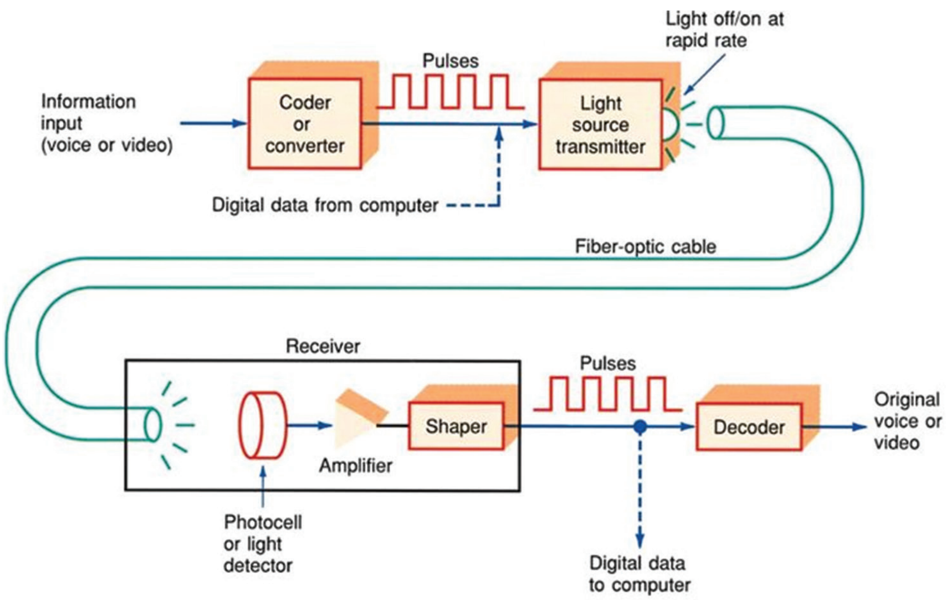

Fig. 1. Fiber optics communication system (Winzer, 2014).

property. In Ref. (Clark et al., 2019), the author shows more temperature tolerance variation using hollow-core in very fast fiber-optical communication systems, and the results show the transmission of error-free short packets with less than 625 ps clock recovery time in 25.6 gb/s real-time systems. Finally, in Ref. (Zhu et al., 2019), a comparison was held between the standard single-mode fiber (SMF-28) and the sensitivity of the thermal phase for hollow-core fiber (HCF) 180°C up to room temperature. The results show that temperature changes affect the thermal phase sensitivity of fibers without any coating, whereas HCF is fully insensitive to small temperature fluctuations.

III. Optical Network Structure

This section will present a fully comprehensive discussion of the optical fiber network structure and its properties.

A. Properties of Optical Signal Distribution

As usual, the light is the main source of the fiber optics, which generates the optical signal, where the light is an electromagnetic wave as a part of the electromagnetic spectrum. The main characteristics of electromagnetic waves are wavelength, frequency, and energy. The electromagnetic spectrum contains light waves (visible light), radio waves, microwaves, infrared rays, UV rays, Gama rays, and x-rays (Gurevich et al., 2018). Fig. 2 shows the various bands of light waves, such as the ray (incoherent) or beam (coherent) (Zhang et al., 2019).

The propagation of the light distribution through the medium counts on Snell's Law, by describing the refraction relationship between two materials' different refractive indexes, as shown by equation (1) (Stigloher et al., 2016).

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \quad (1)$$

Where n1 and n2 are refractive index for incident medium1 and refracted medium2, respectively, ϕ1 and ϕ2 are incident angle and refracted angle, respectively, as shown in Fig. 3 (Xu et al., 2019). Hence, the light will be distributed among

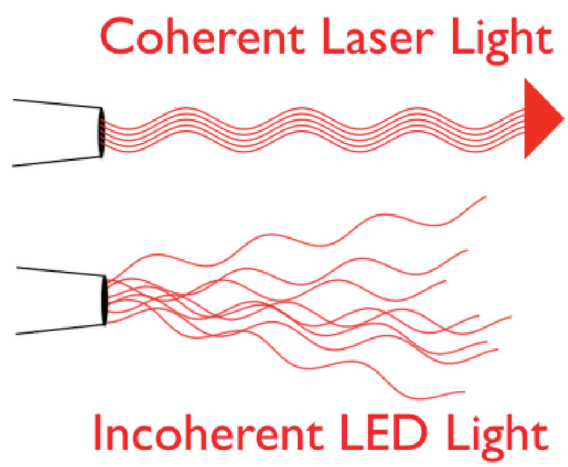

Fig. 2. Coherent versus incoherent light wave (Zhang et al., 2019).

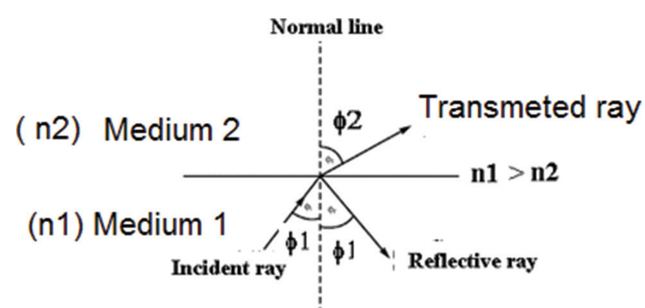

Fig. 3. Light ray behavior (refraction and reflection at a material surface (Xu et al, 2019)).

the several materials, and this distribution depends on the variable value of the incident angle of the light layers (material).

The principle of light travel in any material depends on how fast it travels, whether it is insulating or dielectric on entering. Hence, the light goes through any material at a slow speed, and the percentage of this decrease depends on the value of the refractive index material of the medium. The speed of light in the material denoted by (v) is less than the speed of light in a vacuum (c). Moreover, the ratio of light speed in the vacuum over the light speed in the material will give a value of the refractive index (n) of the material as given by equation (2) (11).

$$n = \frac{c}{v} \tag{2}$$

B. Light Behavior and Dispersion

When the incident angle increases, the refracted angle will also increase until the refracted ray is parallel to the horizontal axis, and any increase after that will result in total reflection and the angle called the critical angle. This case is called total internal reflection (Martin-Fernandez et al., 2013), as shown in Fig. 4.

This case happens in the fiber optics, whereas the light transmuting throws it; therefore, there will be multiple refractions and reflections that produce an aberration and dispersion in the optics signal. To understand the dispersion, we have to imagine two light rays incident on the fiber with different incident angles (ray B perpendicular on the fiber into the center of the fiber (core) and ray A inclined), whereas the fiber has multi-material (refractive index); therefore, the two rays will move inside the fiber, but with the various optical paths, that means the ray A will reach the end fiber faster than ray B. Due to this, the different separation between ray A and ray B is called dispersion (Potsaid et al., Thorlabs Inc., 2015), as it is shown in Fig. 5.

The fiber optic has a different layer of refractive index, distributed as a radial distribution; therefore, when light is incident on the fiber, it will move inside the fiber (by multiple refractions) until it reaches the end with dispersion. Because each ray has its own optical path and they will not be reached (to the end of the fiber) at the same time, the difference in the time of the ray moving is equal to Δt (Keiser, 2006), so Δt is equal to:

$$\Delta = \frac{Ln}{(cn_2)(n_1 \quad n_2)} \tag{3}$$

Where n1 and n2 are the refractive indexes of the first and second materials, L is the length of the fiber optics, and S is the speed of the light in the vacuum.

In general, the dispersion will be various in fiber optics, whether it is single-mode or multi-mode fiber (which are two types of fiber optics) (Sabitu et al., 2019), as shown in Fig. 6.

C. Fiber-Optical Communication Network

The components of fiber optics will be of two types: Active and passive, such as an optical amplifier, coupler, splitter, and multiplexer (Wavelength Division Multiplexing [WDM] and DE). The difference between passive optical

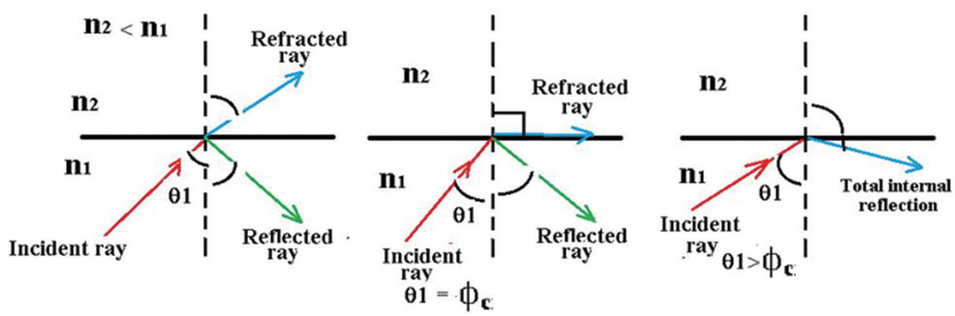

Fig. 4. A critical angle behavior (Martin-Fernandez et al., 2013).

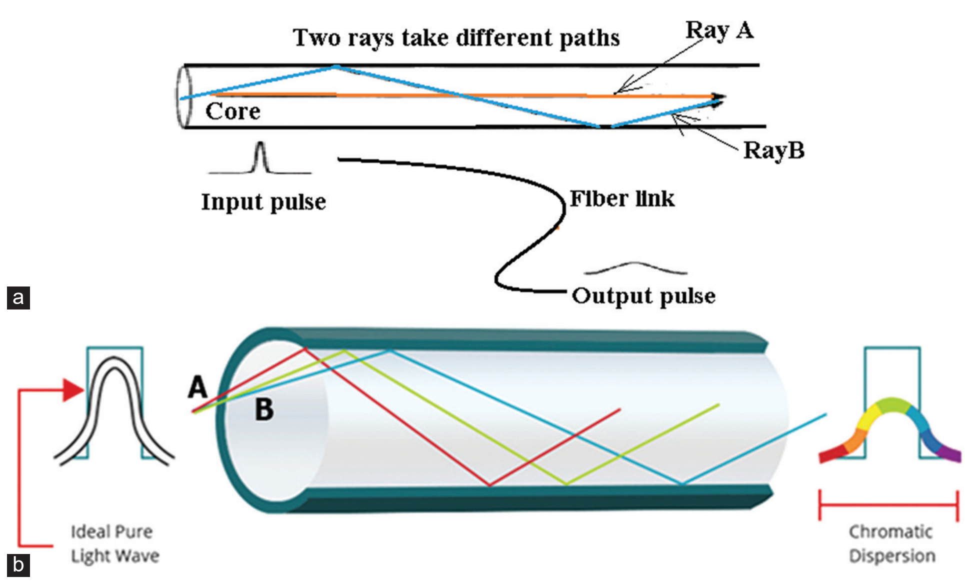

Fig. 5. Dispersion in fiber optics (Potsaid et al., Thorlabs Inc., 2015).

components and active optical components is that the passive will work without external power, whereas the action will not work without external power (Agrawal 2012).

The network is important to share resources and digital information (Marrogy, 2020). For a long period, a fiber-optic network is used to transmute large-capacity information. Moreover, backbone networks use optical fibers due to their ability to transmit high-speed data of more than 10,000 Mbps (10 Gbps) and provide very high spectrum bandwidth.

The network of fiber optics has been used across the countries to transmute huge amounts of information, as well as the fiber-optic network, which is used in many fields and areas such as broadcasting, military, space, and industry. Fig. 7 shows the optical fiber communication networks (Lam et al., 2010).

D. Fiber-Optic Routers

To connect networks with different local area networks, routers are needed to join and merge various subnets with IP addresses counting on the network. There are different types of routers depending on their purpose, such as core, enterprise, edge, branch, and routing protocols (Qasmarrogy and Almashhadani, 2020).

A router of fiber looks like a gateway that connects two or more networks. There is no limitation to using several routers; it may be possible to use 100 routers or repeaters in one package, such as the OSI model, and usually, a router will be in layer 3 of the optical link layers.

Mainly fiber routers connected to ISP modems. They are used to connect the backbone of the internet as they have fast port connections and can forward a huge amount of data between networks, whereas a wireless router can be connected to standard devices.

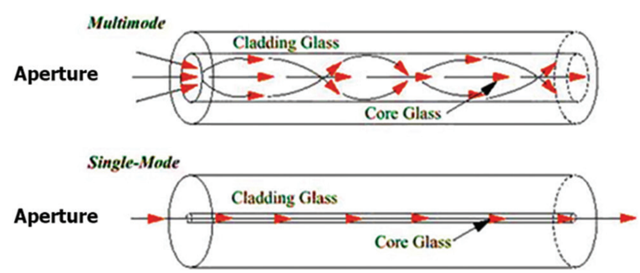

Fig. 6. Structure of fiber optics mode (Sabitu et al., 2019).

E. WDM System

The WDM is a type of optical multiplexer that is a wavelength deviation multiplexer and is used with optical communication. Its basic structure is shown in Fig. 8. It offers a boost to the transmission capacity of the fiber. The function of WDM is to accept multiple independent wavelength sources (with a small difference between them) and then transmit them in one narrow spectral band in the same fiber without any effect on the information. Hence, this processing “sometimes” is called a dense WDM (DWDM).

The advantage of DWDM is that it is wavelength spaced properly to avoid channel interference adjusting because if interference occurs, it produces distortion in the optical signal. This distortion refers to the difference between the beam center wavelength of the light and the characteristics of spectral operating from other optical components (The reasons for this case are the time and temperature). Furthermore, the distortion produces the dispersion or drift in the pulse of the optical signal; if this dispersion is not treated, it will cause the wavelength to trespass into another spectral band region. (Richter et al., 2013). As shown in Fig. 9. Ther Chromatic WDM Application on FTTA with a Guard Band Between Wavelength Channels as an operations safety factor.

F. Fiber-Optic Cable

Fiber-optic cable contains several single fibers, whereas each single fiber structure is from the center (middle of the fiber) a core surrounded by cladding and then buffer coating (jacket). The core is made of a sort of glass (number of layers; each layer has a value of the refractive index (n), distributed as radially as shown in Fig. 10), which illustrates a cable of optical fiber with six suboptical cables (called loose tubes) that contain six optical fibers with a diameter of 250 μm. Hence, the light (with information) will be transmitted in every single optical fiber inside the core by optical carrier waves, whereas the cladding keeps the optical signal inside the core by processing what is called total internal reflection, as shown in Fig. 11 (Chang, Senko Advanced Components Inc., 2016).

When the light travels in fiber optics, some of the speed will be changed due to the rays’ refraction during passing through the variable refractive index (n) of the material, according to Snell’s law (eq. (1)), where n is the ratio

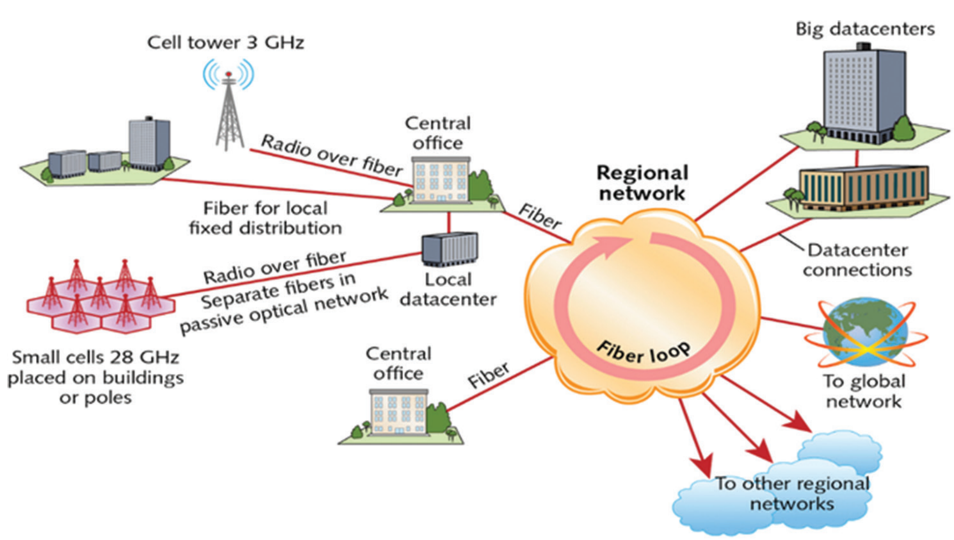

Fig. 7. Fiber optics networks (Lam et al., 2010).

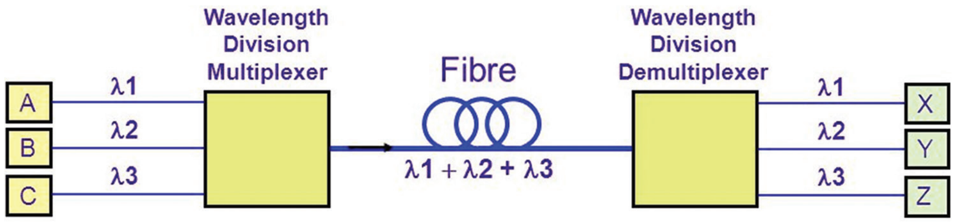

Fig. 8. WDM technology diagram (Winzer, 2012).

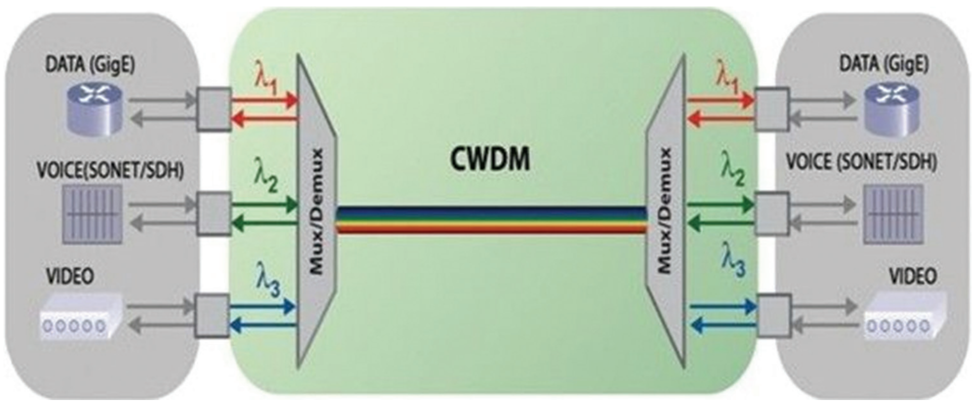

Fig. 9. CWDM application on FTTA (Richter et al., 2013).

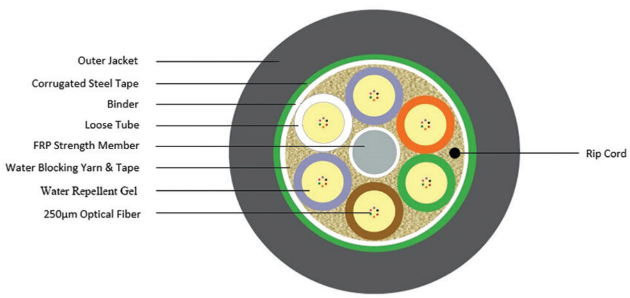

Fig. 10. Layers of pica fiber cable (Chang, Senko Advanced Components Inc., 2016).

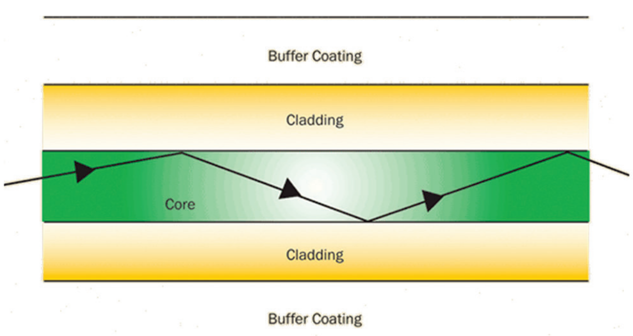

Fig. 11. Transmitting of optical signal in a fiber optic by applying refraction and reflection laws (Chang, Senko Advanced Components Inc., 2016).

between the speed of light in the vacuum (c) and the speed of the light in the material (v). As usual, the speed of the light will be reduced because the light will intersect with the particles (molecules) of the materials. This reason will produce some absorption, and the others will be scattered. In this case, it is fair to treat it using an optical amplifier to raise the power and re-transmitting the optical signal again into the fiber optics, as shown in Fig. 11.

IV. Fiber Optic and Variable Temperature Effects

The effect of variable temperature degrees will be on the thermal expansion value of the optical component material, that is, it affects the shape coefficient (q) and position coefficient (p) (Jamieson, 1981).

Whereas (q) depends on the radius of curvature value for the optical component surface and (p) depends on the value of the object and image distance (Li et al., 2020).

The change in the values of p and q will transfer indirectly to the focal length (f) values because any change in the refractive index (n) of the optical component material will change the values of p and q. Therefore, f can be calculated from the following equation (Jamieson, 1981):

$$f = \frac{K}{(n-1)} \tag{4}$$

Whereas K is a geometrical constant, for any variable in the ratio of the variable of refractive index to the variable of focal length, any variable in temperature (dT) will be a variable in refractive index (dn), which means a change in the speed of the light in the material, which causes more dispersion and distortion (Li et al., 2020). Therefore, (Jamieson, 1981)

$$\frac{\partial f}{\partial n} = \frac{K}{(n-1)^2} \tag{5}$$

Finally, any change in the value of focal length will be a change in the shape of the focal point (causing defocus or a distorted image), the variable in the focal length () (Jamieson, 1981), as follows:

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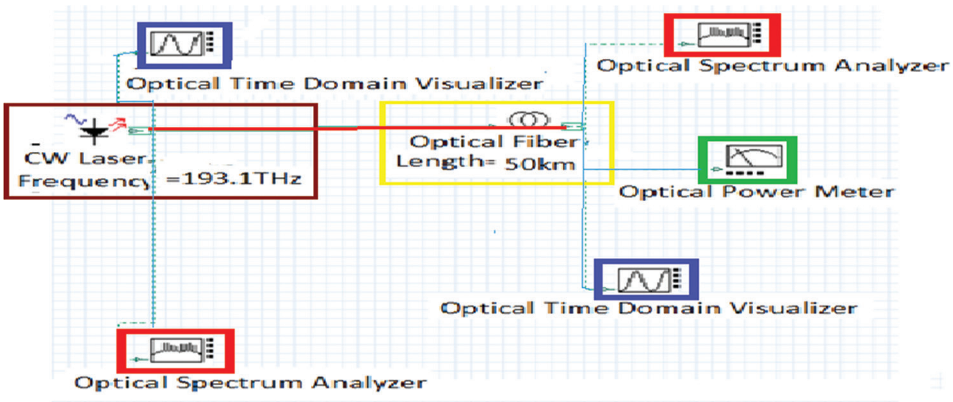

Fig. 12. Practical diagram of optical fiber connection (using Optisystem15).

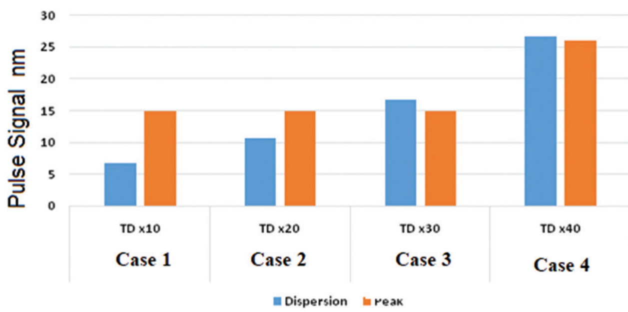

Fig. 13. Dispersion and peak power values.

$$\Delta f = \frac{\Delta n K}{(n-1)^2} \tag{6}$$

V. Results and Discussion

Using the simulation program (Optisystem 15) to setup the simulated circuit, as shown in Fig. 12, simulating the circuit with different random values of the dispersion according to variable values of temperature degree. For each run, the output was recorded for both Optical Time Domain Visualize and Optical Spectrum Analyzer, and the simulation parameters are shown in Table I.

Therefore, four main values of dispersions have been taken (according to the value of temperature), as shown in the following Table II.

Figs. 13–15 show the results histogram of Table II data. Fig. 13 shows the relation between dispersion value and peak power with pulse signal for each case (1, 2, 3, and 4). Whereas the Fig. 14 shows the behavior of bandwidth for variable temperatures, and Fig. 15 shows the relationship between pulse signals for variable temperatures.

Fig. 16 shows the spot diagram at the image plane of the fiber optics (we used the simulation program "ZEMAX OpoticStudio") for two cases: the first without the temperature effect and the second with the temperature effect. It is the effect of temperature on spot distribution (where the spot is defined as the interaction of the number of rays (output rays) with the image plane, and the size and intensity of the spot depend on the number of rays that interact with

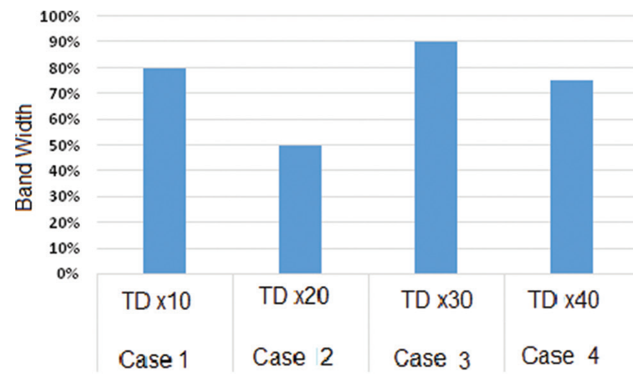

Fig. 14. Bandwidth values.

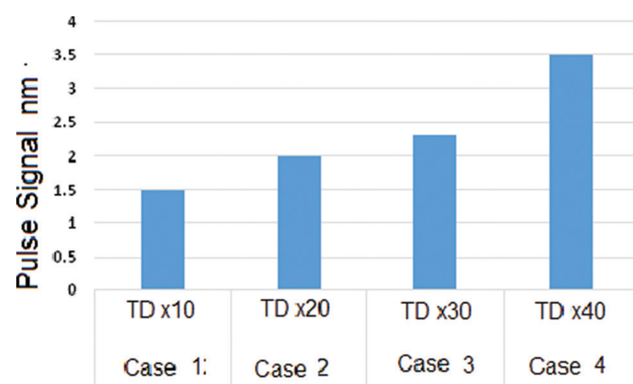

Fig. 15. Pulse signal values.

TABLE I
Simulation Parameters

Parameters	Values
Fiber-optic cable	Single-mode
Fiber-optic length	50 km
Signal frequency	193.1 THz
Sample rate	64×10^{10} H
Sequence length	128 bits
Sample per bit	64
Number of samples	8192
Linewidth	10 MHz

the image plane). Whereas Fig. 17 shows the behavior of spot distribution for cases without a temperature effect,

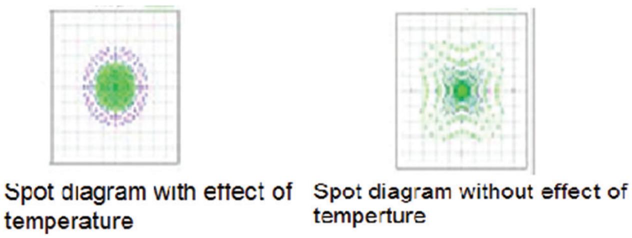

Fig. 16. Spot diagram at image plane (using the simulation ZEMAX).

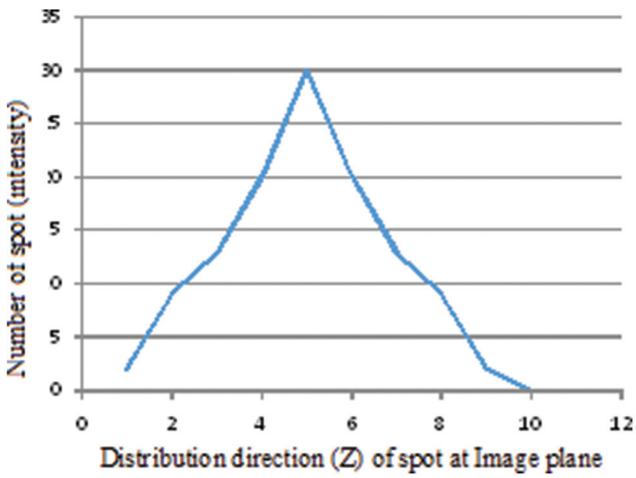

Fig. 17. The spot diagram distribution at image plane without effect of temperature.

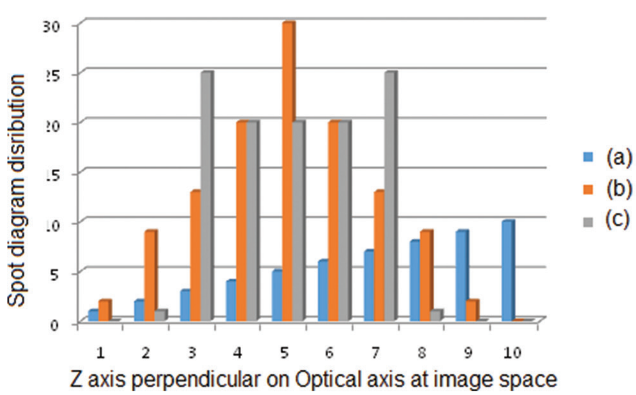

Fig. 18. Histogram shows the spot diagram distribution for (a) linear distribution, (b) normal distribution (without temperature effect), and (c) spot distribution (with temperature effect).

Fig. 18 shows the spot distribution for three cases: the first is for liner distribution, which means the distribution from the outer image plane to the center of it; the second is for a normal spot diagram without a temperature effect; and the third is for spot distribution with a temperature effect.

By analyzing the output of the Figs. 19–22, which are the result of using the simulation program (Optisystem 15). The figures displayed the output of (visualize instruments) "Optical Spectrum Analysis" and "Optical Time Domain." In Fig. 19, the dispersion value is the minimum value, whereas it increases randomly until Fig. 22 has the maximum value of dispersion. The bandwidth of optical spectrum analysis

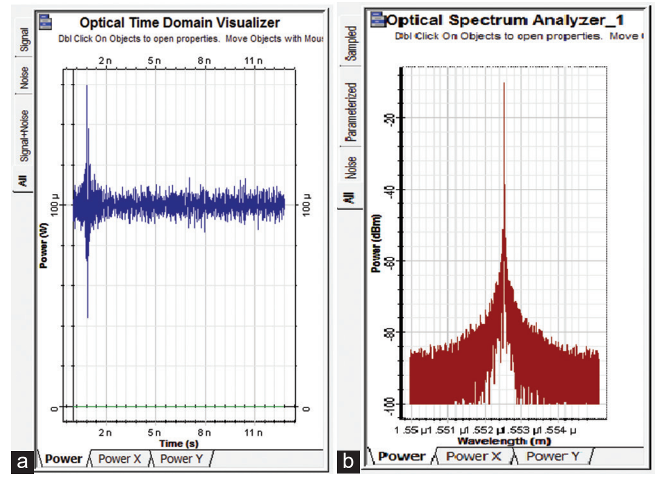

Fig. 19. Case 1 (a) optical time domain visualizer and (b) optical spectrum analyzer (Using Optisystem 15).

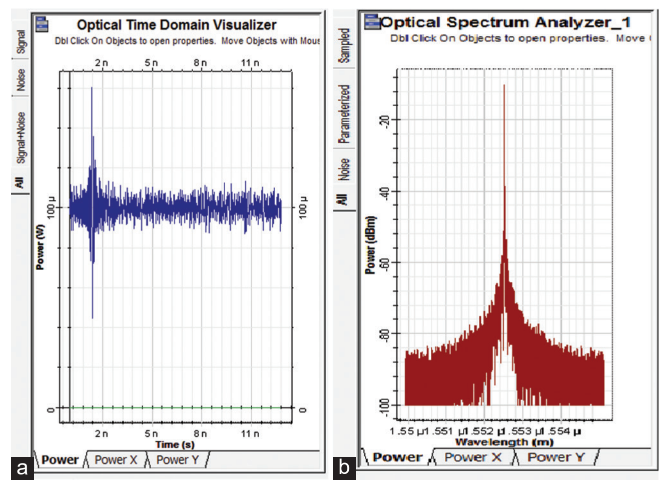

Fig. 20. Case 2 (a) Optical time domain visualizer and (b) optical spectrum analyzer.

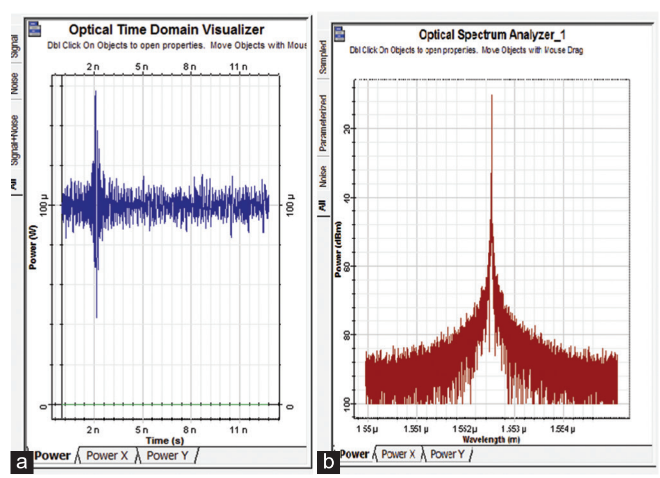

Fig. 21. Case 3 (a) Optical time domain visualizer and (b) optical spectrum analyzer.

is variable, depending on the dispersion value, which was affected by the thermal temperature. And for the "optical time domain," the pulse of the signal was moved from the minimum value (1.5 nm), as shown in Fig. 19, to get the

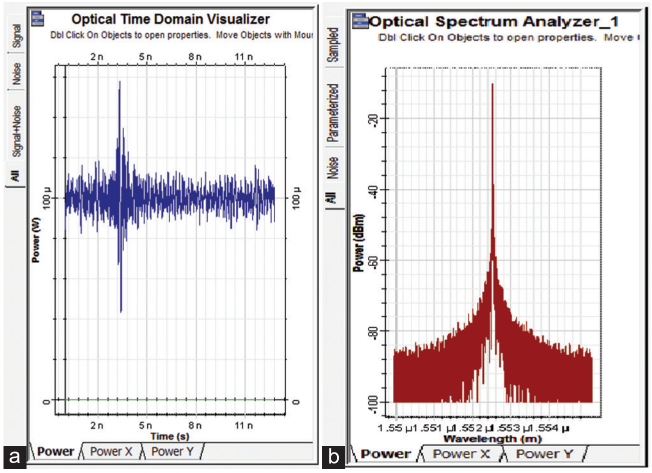

Fig. 22. Case 4 (a) Optical time domain visualizer and (b) optical spectrum analyzer.

TABLE II
Dispersion Values

Temp. K° T_D	Dispersion	Bandwidth	Peak	Case number	Pulse signal
T_D×10	6.75	80%	15	1	1.5 nm
T_D×20	10.70	50%	15	2	2 nm
T_D×30	16.75	90%	15	3	2.3 nm
T_D×40	26.75	75%	26	4	3.5 nm

maximum value in Fig. 22 is 32.5 nm due to the variable value of dispersion.

VI. Conclusion

1. As a conclusion, we can see that the thermal effect on the fiber optics signal takes place during the thermal expansion of the fiber optics material.
2. Of course, the effect of temperature variables on the optical signal distribution is clear during the distribution of the spot diagram.
3. The effect will transfer to the dispersion value of the fiber optics.
4. The effective value of thermal is not clear in fiber optics because there are different types of material (that means different refractive index and different thermal expansion for each one) in fiber optics. The reason for the thermal effect will be distributed between the material layers.
5. The amount of the temperature variable does not linearly affect the fiber optics signal because there are many productions against the extra effect, such as temperature and force.
6. The thermal effect will be less in fiber cable than in single fiber. Because there is a double jacket coating on the cable than in single fiber. Furthermore, there is an outer PVC jacket on the cable.
7. The variable in the dispersion value does not have the same effect on the optical image form as an optical signal. Because the tolerance value of imaging is higher than that of the optical signal. Furthermore, the effect of the dispersion value (which happens due to the thermal effect) is not clear; for each fiber optics manufacturing, there will be some acceptance value of dispersion that does not affect the optical signal (which is within the manufacturing tolerance).
8. Using the Optisystem simulation program is useful for designing and analyzing optical fiber systems.

Using the ZEMAX optical simulation program is useful for designing and analyzing geometrical optics.

For future work, we suggest implementing all the work practically to test more values and get more realistic results.

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