مجلة جمعية الليزر العراقية
Iraqi Laser Society Journal
I.L.S.J.

Issue-1 3rd Year 2026

Enhancement the Propagation Properties of Optical Fiber Communication Links Using Core Doped Optical Fibers

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Abstract

The increasing applications for modern optical fibers present significant challenges to the material properties and the processing technology of fiber optics. These types of optical fibers had many applications in optical fiber communication system and sensing devices. This work studied the transmission properties of core-doped single-mode fiber with different materials doping. Two doping materials were used, germanium and thallium, with different communication link lengths (1 and 15) meters. This work studied Full Width of Half Maximum (FWHM) and dispersion. The results clearly show that the doping material decreases the broadening of the Gaussian propagation pulse and thus decreases dispersion. This influence was more apparent in optical fibers doped with thallium than germanium.

Keywords: Keywords: Ge- doped optical fiber; Optical Fiber Communication Systems; Thallium doped optical fiber.

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I.L.S.J.
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تحسين خصائص الانتشار وصلات الاتصالات بالألياف البصرية باستخدام الالياف البصرية ذات القلب المشوب

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الخلاصة

تمثل التطبيقات المتزايدة للألياف البصرية الحديثة تحديات كبيرة لخصائص المواد وتكنولوجيا معالجة الألياف البصرية واهميتها في تطبيقات الاتصالات وأجهزة الاستشعار البصري. في هذا العمل سيتم دراسة خصائص الإرسال للألياف أحادية النمط ذات القلب المشوب بمواد مختلفة. تم استخدام مادتين للتطعيم هما الجرمانيوم والثاليوم مع أطوال وصلة اتصال مختلفة (1 و 15) م. في هذا العمل تم دراسة عاملين وهما: العرض الكامل لنصف الحد الأقصى FWHM والتشتت. اظهرت النتائج بوضوح أن مادة التطعيم تقلل من اتساع نبضة الانتشار الغاوسية وبالتالي تقلل التشتت. كان هذا التأثير أكثر وضوحًا في الألياف الضوئية المطعمة بالثاليوم من الجرمانيوم.

الكلمات المفتاحية: الالياف الضوئية المطعمة بالجريمانيوم؛ انظمة الاتصالات بالالياف الضوئية؛ الالياف الضوئية المطعمة بالثاليوم.

Introduction:

Optical fiber communication technology forms the backbone of modern high-speed internet access, both for fixed fiber networks and mobile communication systems. It has enabled the rapid expansion of data transmission capabilities, supporting the growing demands of users worldwide. Optical fibers have revolutionized long-distance communication, allowing for ultra-high-capacity connections that span continents and even oceans. This capability is vital for global data exchange, international business, and the functioning of the internet [1]. Over the past two decades, there has been a remarkable increase in the transmission capacity of optical fiber systems. This increase is attributed to advancements in various aspects of the technology, including the development of more efficient optical components, signal processing techniques, and the use of wavelength-division multiplexing (WDM). Despite the substantial progress, there is recognition within the field that there is a fundamental limit to the transmission capacity of systems based on conventional single-core single-mode optical fiber. This limit is projected to be on the order of 100 terabits per second (Tb/s)[2].

To enable total internal reflection of light within the optical fiber, silica must be doped with different elements or materials to achieve a higher refractive index in the core region compared to the cladding. This refractive index difference is what allows light to be guided along the core of the fiber by reflecting it off the core-cladding interface. The doping of silica fibers can be tailored to achieve specific optical properties, making them suitable for different applications such as telecommunications: Silica optical fibers used in telecommunications typically have a core doped with germanium (Ge) or other elements to increase its refractive index, allowing for efficient transmission of light signals over long distances. The low optical loss and high bandwidth of silica fibers make them ideal for transmitting data in the form of light pulses, enabling high-speed and long-distance communication. Sensing applications is also very important application of optical fibers the choice of dopants and fiber design can be customized to optimize sensitivity to specific environmental factors like temperature, pressure, strain, or chemical changes. By altering the doping profile and geometry of the fiber, it's possible to create sensors that respond to changes in these parameters, making them valuable for monitoring and detecting various conditions [3].

The doped structure can be identified either below or above the coordinated atoms. This suggests that dopant materials can be incorporated into the structure of the material in different ways. Different types of dopant materials are mentioned, such as substitutional or interstitial dopants like Cl (chlorine) or H (hydrogen). Substitutional dopants replace atoms within the crystal lattice, while interstitial dopants occupy spaces between lattice sites. The ransparency of glass or fibers. Doping can lead to changes in the absorption bands within the bandgap of the material, which in turn can affect its transparency to light. Defects in the material can be created either directly due to radiation exposure or because of the anufacturing process. These defects may serve specific purposes or have an impact on the material's properties. The fiber doping profile had to be optimized. This optimization is aimed at defining the guided modes within the fiber, the confinement factor, and the sensing properties. It also mentions the Brillouin signature, which is related to the scattering of light in a material. Also lowering attenuation involves reducing absorption of light and minimizing Rayleigh scattering, which are sources of signal loss. For these reasons, the common doping elements (named dopants or codopants) are quite limited in number for passive optical fibers: germanium (Ge), fluorine (F), boron (B), phosphorus (P), aluminum (Al) and nitrogen (N) [4]. Most of the telecom-grade optical fibers possess a Ge-doped core and either a pure silica cladding or a cladding doped with a combination between the Ge, P and F dopants. Phosphorus and Aluminum dopants are commonly used in the core of active optical fibers. They serve the purpose of reducing the clustering of rare-earth ions such as Erbium (Er3+) and Ytterbium (Yb3+). This reduction in clustering helps enhance the performance of fiber-based amplifiers or lasers that rely on these rare-earth ions for amplification or lasing. fibers containing either aluminum (Al) or phosphorus (P) dopants are highly sensitive to radiation. This sensitivity can be problematic in some applications, but it also makes these fibers suitable for distributed dosimetry techniques, where they can be used to measure radiation exposure. Boron is used in polarization-maintaining optical fibers. Such fibers are designed to maintain the polarization state of light propagating through them. Additionally, boron is used to increase the photosensitivity of germane silicate optical fibers, which makes it easier to write Fiber Bragg Gratings (FBGs) in them. FBGs are used for various sensing and telecommunications applications[4,5]

Most of published articles of this subject focused on the influence of the doping materials on the radiation induced absorption and transmission or laser fiber design analysis. Which is mainly used for the dosimeter application like the study submitted [6] they studied the characterization of the thulium-doped silica optical fibers with increased quantum conversion efficiency (QE). They conclude that despite low QE causing energy storage time reduction and an increase in the laser threshold, it has a negligible effect on the laser's slope efficiency. Laser slope efficiency refers to the efficiency with which the laser converts the pump power into useful laser output. Also, the low QE does not significantly impact this efficiency parameter. And even if the active medium (Tm-doped fiber) has impaired QE efficiency (low QE), it is still possible to build high-power, continuous-wave (CW) Tm-doped fiber lasers. They suggest that other factors or techniques may compensate for the limitations imposed by low QE. The high QE is particularly crucial in other photonic devices, such as ASE (Amplified Spontaneous Emission) sources, low- and moderate-average-power fiber lasers and amplifiers, or Q-switched pulsed sources. In these devices, having high QE is essential for optimal performance. hey studied the advantages or properties of radiation-induced emissions (RIEs) in visible domain using multi- mode fiber doped with nitrogen. This doped fiber is exposed to pulsed X-ray. They also tested this device at lower dose rates associated with steady-state X-ray irradiation machines (up to 100 keV photon energy, mean energy of 40 keV). They found that the RIE of this multimode optical fiber linearly depends on the dose rate over an ultra-wide dose rate range from 10 -2 Gy (SiO2)/s to a few 109 Gy(SiO2)/s and photons with energy in the range from 40 keV to 19 MeV. These results demonstrate the high potential of this form of radiation monitors for beam monitoring at very high dose rates in a very large variety of facilities as future FLASH therapy facilities [7].

In 2022 also two important review articles presented by [8,9] they discussed grating fabrications in polymer optical fibers with photosensitive dopants and recent advances in optical fiber enabled radiation sensors respectively.

Abdul-Rashid et al study the influence of Ge dopants in Ge-doped silica optical fiber scintillators used for radioluminescence (RL) based time-resolved dosimetry, in particular the decay time and RL yield. The Ge-doped silica optical fiber scintillator with large and small core samples represents high and low Ge-dopant contents.

The samples showed linear RL response, with differing memory and afterglow effects. The large core samples, indicative of a higher Ge-doping content and a high number of defects, demonstrate faster decay time and higher RL yield. The results suggest a contribution of Ge-doping in affecting the triplet states of the SiO2 matrix, thereby reducing phosphorescence effects [10].

The submitted work studied the transmission properties and optical fiber dispersion of Germanium-core doped single-mode optical fiber and thallium-core doped single-mode optical fiber. The optical fiber communication length links were 1 meter and 15 meters.

2. Experimental Work

A simple optical fiber communication link has been designed, as shown in figure 1. The transmitter laser source has a wavelength of 1550 nm coupled with single-mode fiber (SMF) (Thorlabs Inc. USA). First, the input link is connected to SMF with different fiber lengths, 1m, and 15 m.

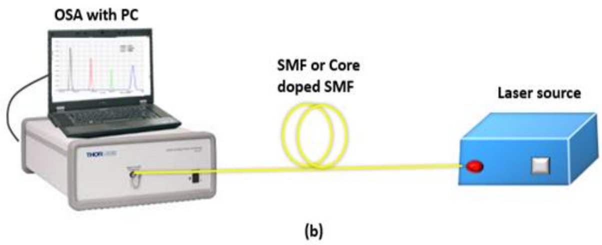


Figure 1. The optical fiber communication link, (a) photographic image, (b) schematic diagram.

Then core doped SMFs were used to study the influence of doping core material on the optical signal properties. Two different core doped SMF were used, Germanium doped optical fiber and Thallium doped optical fibre. These doped optical fibers were purchased from Flexilicate Inc. Malaya figure 2 shows the cross-section of both doped core optical fibers. Also, two different optical fiber lengths were used, 1 m and 15 m. the properties of the doped optical fibers are illustrated in table 1.

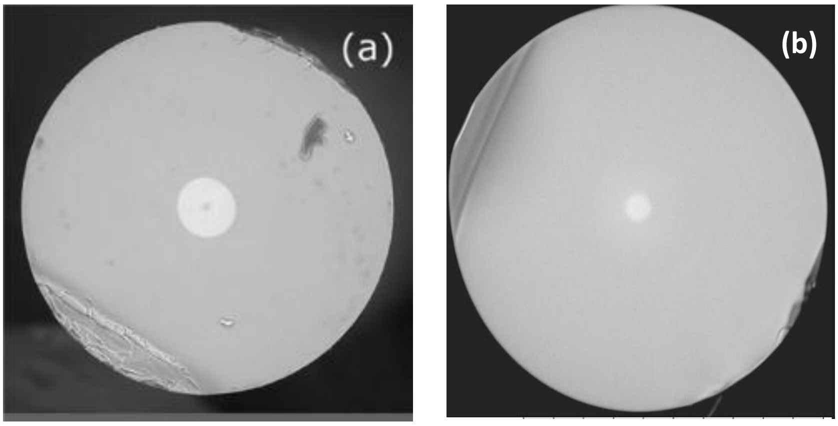


Figure 2. SEM of cross section of optical fibers core doped with (a) thallium, (b) germanium.

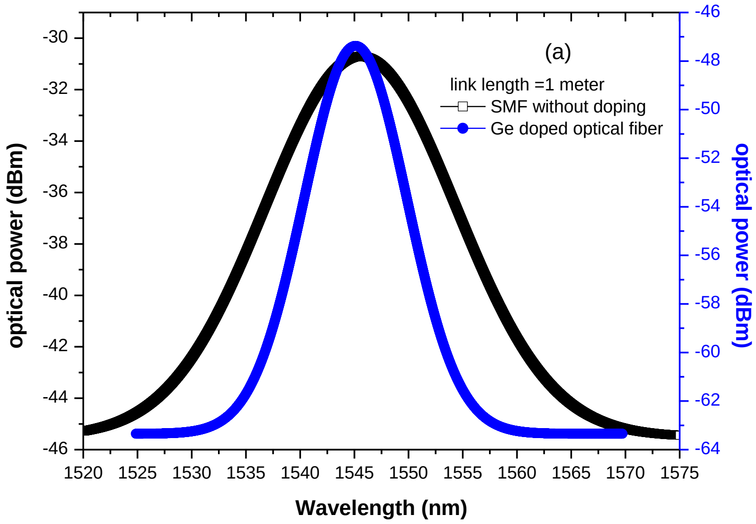
Table 1. Properties of the core doped SMF

Ge-doped fiber	**~0.5 core-to-cladding ratio**
	1 and 15 length (with polymer coating)
	125 µm diameter
	δn= 0.0039
	NA = 0.13
	GeO_2 (mol%) =~ 3.6-4%
Tl-doped fiber	**0.7 core-to-cladding ratio**
	1 and 15 length (with polymer coating)
	δn= 0.0034
	NA = 0.13
	Tl_2O_3 (mol%) =~ 3.8%

1. Results and Discussions

The optical spectra were collected online using the optical spectrum analyzer.
Firstly, the results of all studied cases will be illustrated in the figures below, followed by a discussion of the obtained results.

The optical signals of optical fiber communication link with two lengths, 1 meter and 15 meters, were collected and analyzed. Using commercially available SMF (without doping) and Ge- core doped optical as apparent in figure 3.



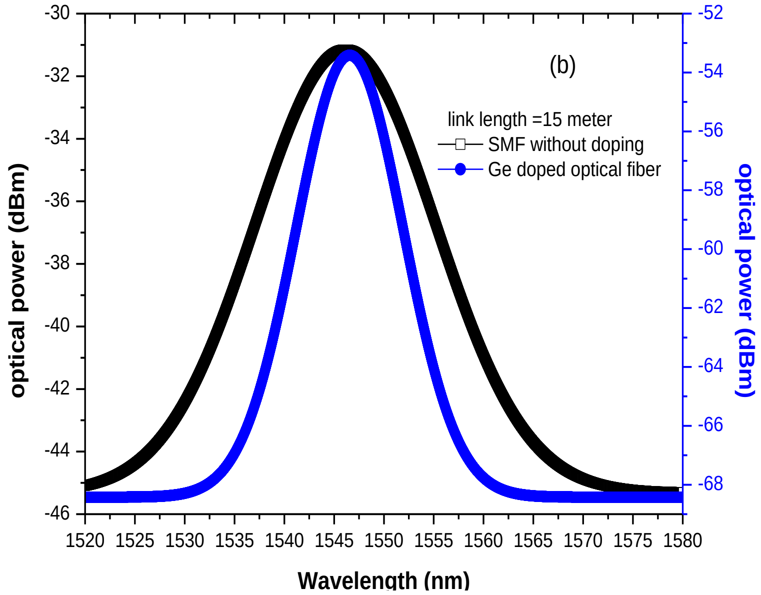


Figure 3. The optical spectra of SMF (without doping) and Ge-core doped core with link length (a) 1m, (b) 15m.

From the figures above, peak wavelength, the full width of half maximum (FWHM), and peak power for each case were measured and calculated. The peak wavelength, FWHM, and peak power

of 1 m fiber length without doping were 1545.569 nm, 9.059nm, and (-) 30.773 dBm, respectively. While for 1m Ge- core doped optical fiber were 1545.112 nm, 4.737nm, and (-) 47.221 dBm. While for 15 m length for optical fiber communication link using fibers without doping, the peak wavelength, FWHM, and peak power were 1546.141 nm, 13.233 nm, and (-) 31.083 dBm, respectively. These values were for the 15 m Ge-core doped optical fibers equal to: 1546.568, 5.3755 nm, and (-) 53.338 dBm, respectively.

The optical spectra of SMF without doping and Tl- core doped optical fiber with communication link lengths (1 and 15) m are illustrated in figure 4.

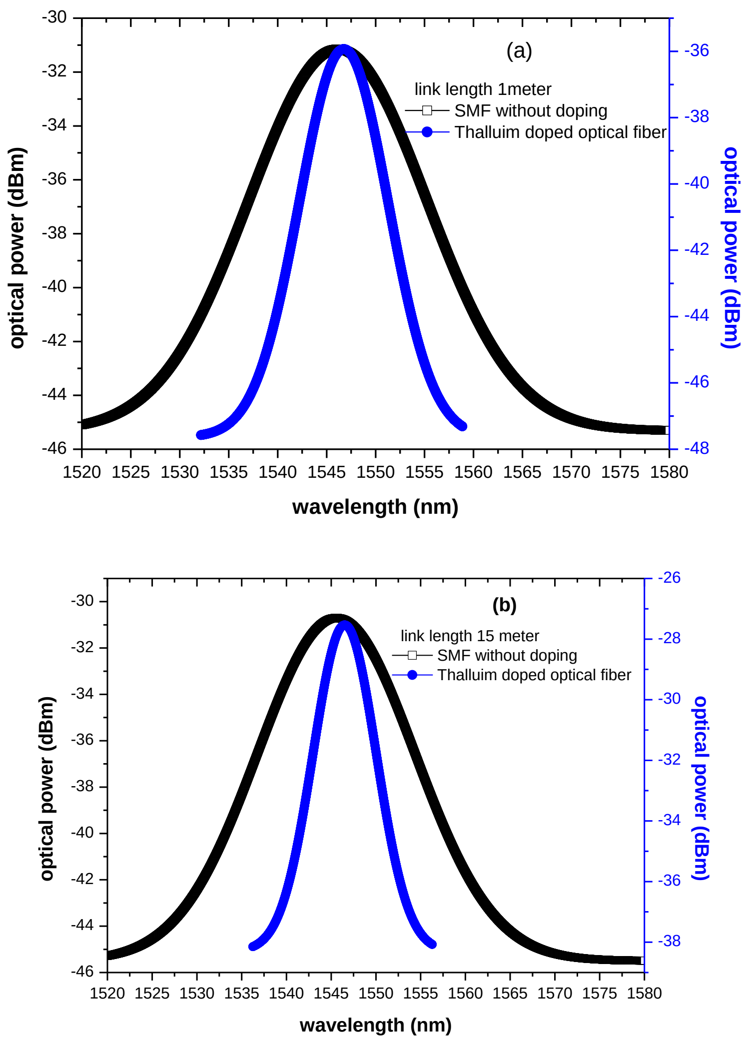


Figure 4. The optical spectra of SMF (without doping) and Tl-core doped core with link length (a) 1m, (b) 15m.

From figure 4, peak wavelength, the full width of half maximum, and peak power for each case were measured and calculated. The peak wavelength, FWHM, and peak power of 1 m fiber length without doping were 1545.569 nm, 9.059nm, and (-) 30.773 dBm, respectively. While for 1m Tl- core doped optical fiber were 1545.112 nm, 4.737nm, and (-) 47.221 dBm.

While for 15 m length for optical fiber communication link using fibers without doping, the peak wavelength, FWHM, and peak power were 1545.569 nm, 9.059 nm, and (-) 30.773dBm, respectively. These values were for the 15 m Tl-core doped optical fibers equal to: 1546.518, 3.450nm, and (-) 36.70 dBm, respectively.

The dispersion of the submitted optical fiber communication links could be calculated due to equation 1 (Al-Douri, 2017):

$$D_\lambda = \frac{s_0}{4(\lambda - \lambda_0^4/\lambda^3)} \qquad (1)$$

Where $D_\lambda = \frac{ps}{nm} Km$ represents the dispersion, and s_0 is a parameter equal to $0.042 \frac{ps}{nm} Km$, and is the corning specifies a range of 1302-1322nm.this number is the average and equal to ($\lambda_0^4 = 1311\ nm$) . And λ is the wavelength of the optical transmitter source which is equal 1550 nm. Table 2 illustrated the dispersion values for all above case studies.

Table 2. The calculated dispersion values.

Optical fiber link type	Mode peak wavelength (nm)	$D_\lambda = \frac{ps}{nm} Km$	Dispersion/distance dBm
1-meter SMF without doping	1545.569	18.402	0.18402
1-meter with Ge- core doped fiber	1545.112	18.418	0.18418
15- meter SMF without doping	1546.141	18.381	0.12254
15- meter with Ge- core doped fiber	1546.568	18.366	0.12244
1- meter SMF without doping	1545.569	18.402	0.18402
1- meter with Tl-core doped fibers	1546.518	18.368	0.18368
15 -meter SMF without doping	1546.141	18.381	0.12254
15 -meter with Tl-core doped fibers	1546.752	18.360	0.1224

From the above figures and table, it could be noticed that the spectral behavior shows a broadening after a pretty long propagation distance which is predicted due to dispersion phenomena. Interestingly, the eventual stable spectrum is still Gaussian.

FWHM shows a rapid increase of 15 meters of propagation link length; after that, the spectral recompression occurs, and the FWHM gradually decreases and eventually tends to a stable value as the propagation distance decrease. When the optical field further propagates to 15 m, owing to the combined effects of Self Phase Modulation (SPM) and Group Velocity Dispersion (GVD), also, it's obvious that there are the blue-shifted frequency components of the peak signal (when the link length is 1 m) and the red-shifted frequency (when the link length is 15 m) the blue-shifted frequency components of the preceding pulse and the red shifted frequency components of the following pulse will overlap at a longer propagation distance. A further study should be done to understand this behavior concerning material science which will be considered in the future.

Conclusions

Material science developments have led to tremendous achievements in optical fiber technology and applications. Optical fiber communication, Fiber lasers and fiber sensors are the most developing applications in this field. Optical fiber communication has revolutionized the way information is transmitted over long distances, offering high bandwidth and low loss characteristics. To further improve the performance of optical fiber communication links, this study explores the use of core-doped optical fibers. By introducing dopants into the core of optical fibers, we aim to enhance various propagation properties, including signal quality, dispersion management, and overall transmission efficiency. This research investigates the impact of different dopant materials and fiber lengths on optical fiber performance and provides insights into their potential applications in advanced communication systems.

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