

# Large Core Germanium Doped Photonic Crystal Fiber Over FMF

Tendai Masunda Zengeni, Chrissanthi Angeli, Roshidi Din, Angela Amphawan

**Abstract**—Hermite Gaussian modes are multiplexed over few mode fiber (FMF) with a Germanium doped large core photonic crystal fiber as a waveguide in a 20Gb system is studied. Comparison with regards to bit error rate (BER) and eye diagram performance is made between the 20Gb Germanium doped system and another system under the same conditions but with an undoped large core PCF. Results will indicate that the Germanium doped system performs more optimally compared to the undoped system in terms of the resultant bit error rate and eye diagrams. This inspires doping as preferably recommended to achieve optimal PCF performance.

**Keywords**— photonic crystal fiber, germanium doped, few mode fiber

## I. Introduction

In 1997 Philip Russell developed photonic crystal fiber (PCF) [1], which has been a result of the continuous evolution of optical fibers throughout the decades. The breakthrough of optical fiber since the 1970s has had such an impact, that it has been incorporated in different industries namely, telecommunications [2], data storage [3], networking [4], industrial/commercial, broadcast/CATV [5], defense [6] government [7] and medical fields [8] where fibers are used as light guides, imaging tools and also as lasers for surgeries. PCF's mechanism is such that it confines the guided mode in its core [9] which is engineered to have a refractive index that is higher than the surrounding periodically distributed air cores. PCF combines the properties of optical fibers and photonic crystals and these unique properties incorporating the photonic band gap make it possible for the confinement of light in the core. PCF is known to achieve zero dispersion [9] therefore affirming its superiority over conventional fibers since it can reduce the effects of intersymbol interference [10] during mode propagation hence transmitting a cleaner signal at the receiver almost identical to the one originally sent at the transmitter.

## II. Background

Higher order transverse modes comprise the Hermite Gaussian (HG) as well as the Laguerre-Gaussian (LG)[11, 12] beams which are derived from

solving the wave equation [13] and are popular in the field of optics and photonics. They come about when there is a deliberate imperfection design and superposition in the laser cavity which would normally excite the fundamental mode [14] also known as the Gaussian beam. The m squared metric ( $M^2$ ) is excellent when comparing the quality of a real beam to that of a, fundamental, theoretical beam.  $M^2$  for a Hermite-Gaussian multi-mode beam is given by equation 1,2,3 from [15].

$$M_x^2 = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} (2n+1) |C_{nm}|^2 \quad (1)$$

$$M_y^2 = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} (2m+1) |C_{nm}|^2 \quad (2)$$

Where  $C_{nm}$  is a weighting factor for each of the  $TEM_{nm}$  modes' electric fields and together are represented by

$$1 = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} C_{nm} \quad (3)$$

Therefore, these three equations are used to calculate the theoretical  $M^2$  of any laser beam with modal composition and weights that are known. Doping the core of the fiber with some index-raising material enhances its capabilities and amplifies its guiding properties. Typical index-raising dopants to name a few are germania ( $GeO_2$ , germanosilicate fibers), phosphorus pentoxide ( $P_2O_5$ , phosphosilicate), and alumina ( $Al_2O_3$ , aluminosilicate). Alternatively, the index of the cladding may be lowered e.g. by fluorine or boron oxide ( $B_2O_3$ ) doping. Index-lowering agents can also be used in the core if other required dopants make the index difference too high. 4 HG modes are multiplexed in the 20Gb MDM system being experimented on, that is HG00, HG01, HG10 and HG11. Mode division multiplexing (MDM) is a technique which allows for more channels than ever before to be exploited in data transmission as it exponentially increases the capacity of a single fiber

by creating spatial routes for modes to carry data signals through light.

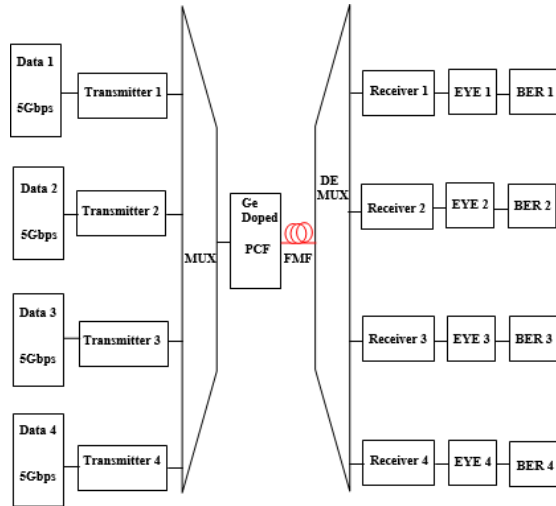


Fig. 1 Schematic diagram of the 20Gb/s MDM system over FMF with Germanium doped PCF used as a waveguide. The same can be applied to the undoped PCF.

The MDM system comprises of 4 pseudorandom binary sequence generators (PRBS) each carrying 5gigabits of data cumulatively making a 20Gb/s system. 4 Electrical generators all with non-return to zero encoders (NRZ) running on current. 4 spatial vertical-cavity surface-emitting lasers VCSELS with a Gaussian beam launched were multiplexed then connected systematically to the germanium doped and undoped PCF which was then linked to a 1 kilometer length few-mode fiber and the transmission medium.

### III. PCF Design

The design process of the PCF in order to get an optimum functioning waveguide is a rigorous process that involves computing modes in different designs of the PCF structure. A Gaussian beam is launched and the modes that are excited are monitored. The maximum total coupled power from the PCF to the MMF should be such that one mode has more power than the rest or at least 3 having the same mode power in order for a satisfactory data transmission process to occur. These structures by way of varying the hole sizes and parameters which include the length, pitch, hole diameter, number of rings, and the launch width and height, we are able to make each design unique and as such it will excite a different number of modes with different modal properties in each computation. Fig 2. Illustrates a few designs created using Rsoft Beamprop software [16] in search for designs to optimize data transmission.

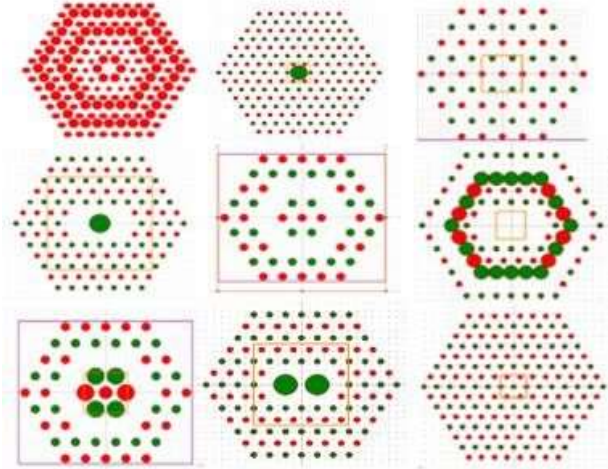


Fig. 2 Several examples of hexagonal PCF designs. Each design will possess unique characteristics in terms of mode confinement, refractive index as well as birefringence.

Since each distinct structure notably generates a unique set of modes with different characteristics and capabilities the 7 ring hexagonal large core design excited 4 modes after mode computation 3 out of 4, which had less than 10% power whilst the fundamental mode coupled about 90% of the power at the receiver. The monitor results against the propagation direction of the Gaussian launch on both structures of the large core Ge-doped and undoped PCF produced the same set of modes with the same powers. During the mode computation, the selected PCF structure computed a total of 4 modes, one which had the highest power at just below 0.9 a.u. and the other three relatively low at less than 0.1a.u. Fig.3 shows the power coupled into the modes HG00, HG01, HG02 and HG03 for undoped PCF and doped Ge-PCF.

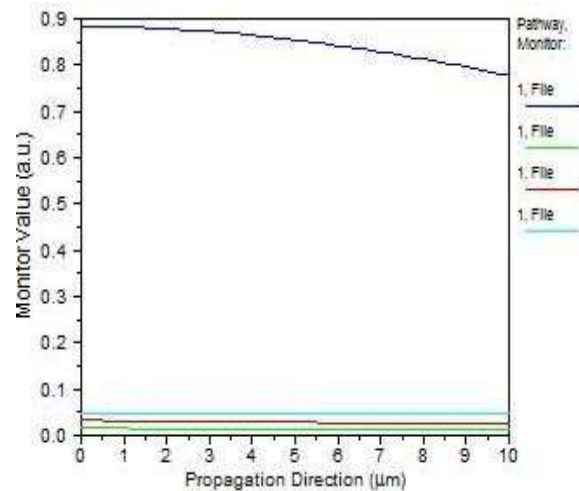


Fig. 3 Power monitoring graph for the 4 computed modes HG00, HG01, HG02 & HG03. for undoped PCF and for doped Ge-PCF

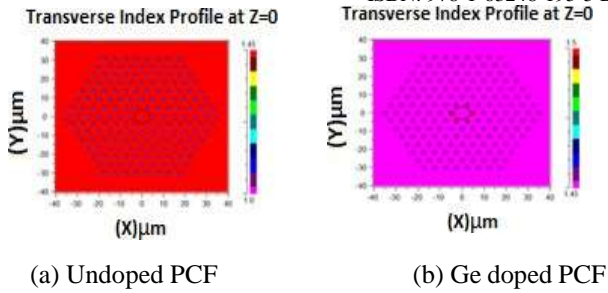


Fig.4 Transverse index profile of undoped and Ge doped PCF

Fig.4 illustrates the transverse index profiles of the undoped as well as the Ge doped PCF both of hexagonal lattice with round holes composed of seven rings and the distinct large core. The background refractive index for the undoped PCF is 1.4 and the refractive index of the airholes is 1.0. On the other hand, the background index for the Ge doped PCF is set at 1.45 and then the core is set at 1.5 because it has a Ge dopant modification.

#### IV. Related Work

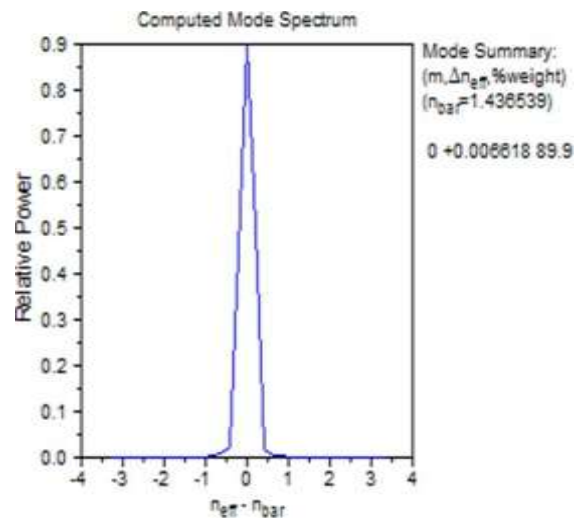
Few mode fiber (FMF) has found a niche in the optical field due to its special ability to increase capacity [17] in optical fiber communications and in future fiber optic networks. Few mode fibers utilize the spatial domain[18] in contrast to single mode fibers which only transmit in single mode fashion and are subject to the nonlinear Shannon's limit, which is the ultimate spectral efficiency threshold that a single mode fiber can reach. FMFs have been eyed as the solution to single mode fibers [19] which will in the near future. Few mode fibers are effective in mode division multiplexing (MDM) as stated in [20] and other emerging applications. Besides multiplexing, they have also been used in sensing [21]. FMF is different from MMF not only in the number of modes but also in the number of available data channels that can be transmitted [22]. FMF carries fewer guided modes up to a few tens, and each mode is treated as an individual data channel in the MDM process. In contrast, the number of modes in MMF is a few hundred [23], and all the modes combined serve as a single data channel in MMF transmission systems.

Photonic crystal fiber in [24] had its inner core doped with Germanium to achieve high negative dispersion, whereas [25] doped the PCF to achieve high birefringence. Germanium is used as a dopant in order to enhance or amplify the capabilities of a photonic crystal fiber. Germanium was used in [26] in the core in order to allow for the inscription of periodic waveguide gratings to test photosensitivity of the structure. A fiber amplifier is also created in [27] with high-index germanium-doped rods. In optical communication, the core of the fiber generally has a higher average refractive index compared to the

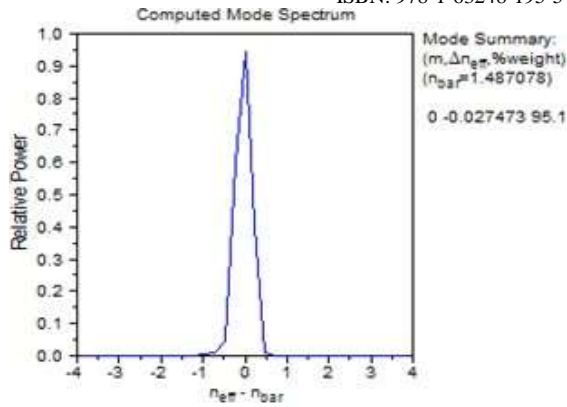
cladding in order to obtain total internal reflection. The effects of adding dopants to the core or to the cladding effectively changes the refractive index values therefore assists in mode confinement and mode redirection as well as mode excitation.

#### v. Results

The computed mode spectrum Fig.5, for both the doped and undoped PCF for this structure illustrates that the design achieves more than 85% retention of power going into the modes after propagation to ensure that as much power as possible is coupled into one mode for effective data transmission. The Germanium doped PCF couples up to 95% of the total power whilst the undoped channels 89.9%. Fig.6 and Fig.7 shows the results of the eye diagrams connected to each receiver in the MDM system, both doped and undoped. The eyes are all open which translates to the radial mode separation increasing, whilst the time deviation between propagation modes decreases[28] hence widening the eye opening. However, Fig.7 is open wider than Fig.6, this is consistent with the bit error rate (BER) as a consequence of the transmission efficiency. The BER and the eye diagrams are complementary when comparison of the channel impulse response is being made. The Ge doped PCF achieved a BER of  $2 \times 10^{-26}$  and the undoped PCF had a BER of  $7 \times 10^{-9}$  concluding that doping the PCF with Germanium achieved better BER therefore better performance during data transmission.



(a)



(b)

Fig 5. Computed mode spectrum from the 2 structures (a) of the undoped PCF and (b) the doped Ge-PCF

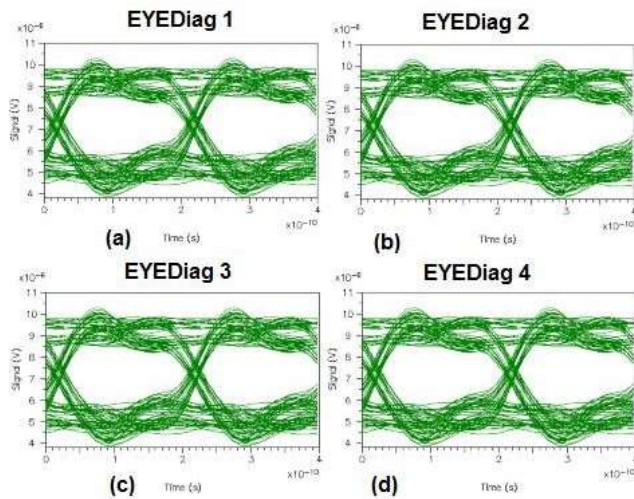


Fig 6. Eye diagrams (a),(b),(c), and (d) from the 4 receivers in the undoped MDM system

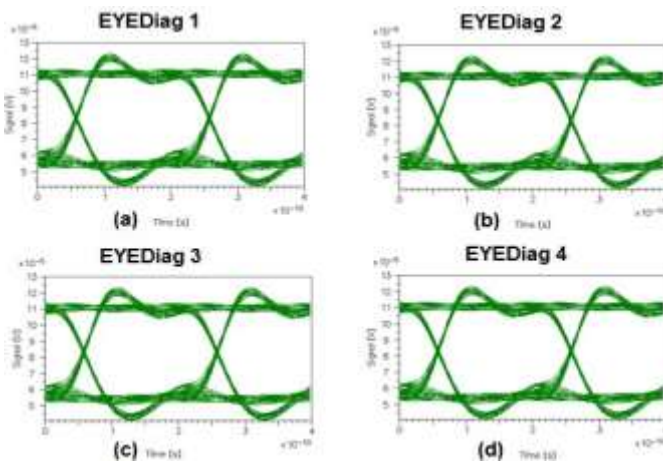


Fig 7. Eye diagrams (a),(b),(c), and (d) from the 4 receivers in the GE-doped MDM system

## VI. Conclusion

Multiplexing Hermite Gaussian modes over few mode fiber in conjunction with a Germanium doped large core photonic crystal fiber yielded better results compared to an undoped PCF used as a waveguide. A 20Gb system was used to gauge the bit error rate and eye diagram performance between the 20Gb Germanium doped system and an undoped system. The Germanium doped system achieved better results compared to the undoped system in terms of the resultant bit error rate and eye diagrams which reinforces the GE doping mechanism as one of the most recommended techniques to increase PCF performance and ultimately improve data transmission capabilities of optic fiber.

## VII. Acknowledgement

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