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Tapered waveguide design for mode conversion in mode division multiplexing (MDM)

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In this paper, the tapered waveguide design was used in mode division multiplexing (MDM) as a mode converter. It was investigated to be used for switching purposes in short haul communication in a data centre. This paper shows the results of a Gaussian beam being converted into transverse modes and vice versa. It also shows the multiplexed version of the modes being converted into a specific target mode. There are two and three combinations of multiplexed modes in the tapered waveguide design, with modes computed as well as converted into targeted modes. The reason for this experiment is to accomplish the goal of replacing opto-electronic switches at data centres into an all-optical switching mechanism. Therefore, this design will enable the processing of large amounts of data using optical switching apparatus by creating additional data channels. It results in providing an all-optical mode conversion switch that incorporates high speed routing of data from one server into another data centre.

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Keywords: Mode conversion, Tapered waveguide, Mode division multiplexing

1. Introduction

A new era has come that is known as the Industry 4.0, which is a name given to the current trend of automation and data exchange in manufacturing technologies which includes cyber-physical systems, the Internet of Things (IoT), cloud computing and cognitive computing [1] [2] [3] [4]. It is known as the fourth industrial revolution [5] as it fosters a “smart factory” which communicates and cooperates with each other and also with humans in real-time both internally and across organizations and offers services and usage by participants of the value chain [1]. There are four design principles in the Industry 4.0, which are interconnection, information transparency, technical assistance, and decentralized decisions. Each of these principles involves data transmission. In order to make this trend a success, the speed and efficiency of data transmission must be upgraded. The internet is expanding and the usage is increasing rapidly [6] and the next generation of computing, an upsurge of social media usage [7] and telecommunications systems, complimentary measures to avail higher speed and bandwidth capacity [8] [9] are the core of the solutions. Light propagates faster than the speed of electrons, or the speed of sound. The usage of optical fiber in every data transmitting system is necessary as it provides the required speed for exchanging information. Data centers are the foundation of the internet by essentially facilitating the retrieval, storage, and processing the requests demanded by users worldwide. The growth of the Internet will surely cause traffic resulting in more demand of the bandwidth that is currently being used, and multiplexing schemes such as wavelength division multiplexing (WDM), are reaching the limits of the number of data they can transmit, hence the solution is to use mode division multiplexing, which uses modes as channels since they can carry more data [10] [11]. MDM has become the most recent scheme used in conjunction with other multiplexing schemes such as WDM [12] [13], time division multiplexing (TDM) [14] [10], and frequency division multiplexing (FDM) [15] in order to meet the bandwidth demands due to the growth of the internet, its users, and services over the years. Hence, the current opto-electronic technology [16] will become overwhelmed from the heavy traffic, which is the reason why all optical switches which have an entirely optical anatomy in personal computers as well as in the data centers are being introduced [17] [18] [19].

2. Background

The use of a tapered waveguide has its advantages in terms of miniaturization as well as obtaining certain optical properties that are suitable for applications in telecommunications. The size of the tapered diameter ranges between a few micrometers, which allows a considerable amount of the transmitted power that is propagated through the evanescent field outside the fiber surface. The light travelling through it will also experience high non-linearity effect which is suitable for non-linear optical switching.

A tapered waveguide consists of a single-mode fiber with a reduced diameter at the waist region. The tapering process is done by heating the fiber to its softening temperature while pulling its ends. After tapering, the core of the fiber will become very small and will not be able to confine the light that propagates through it. The light will leak out to the cladding and propagate as cladding modes. This occurs at the core-mode cut off points at the transition regions [20]. This will cause the cladding to become the new core and the external medium becomes the new cladding. Higher order modes will be generated after this cut-off point.

The mode evolution was experimentally observed in [21] where the results showed that the number of modes increases as the diameter decreases up to a certain size. When the diameter of the core of a single-mode fiber is reduced beyond the “core-mode cut off” point, the lowest order core mode spreads out of the cladding and produces higher order modes. This occurs at the point where the V-number of the core cladding interface is given by [22].

$$V_{cc} \approx \sqrt{\frac{2}{\ln S}}\left[1+\frac{0.26}{\ln S}\right]^{\frac{1}{2}} \tag{1}$$

where S is the ratio between the radius of the cladding and the core. The V-number of the core at z-position is:

$$V_{core}(z) = \frac{2\pi r_{core}(z)}{\lambda}\sqrt{\left(n_{core}^2 - n_{cladding}^2\right)} \tag{2}$$

where the n_{core} and the $n_{cladding}$ are the refractive index of the core and the cladding, respectively. The $r_{core}(z)$ is the core radius at position z and λ is the wavelength of the propagation signal. When $V_{core}(z)$ is equal to V_{cc}, the core will no longer be able to confine the light propagated through it. When $V_{core}(z)$ is smaller than the V_{cc}, the light propagates as a cladding mode.

3. Methodology

This project was done by using several software, such as the BeamPROP software, and the MATLAB software. The BeamPROP software was used to design the tapered waveguide, since the software has its own drawing tools and parameter settings. From this design it allows the computation for modes to be done. The modes computed has to be in good shape, which means that it has to be symmetrical, well-shaped with no distortions, and compact especially for the use of data transmission.

In the next stage, the process was done in the MATLAB software where the complex field of the unwanted modes were made. The phase of this complex form was used for each of the source modes and the target modes, respectively. This is to enable it to prepare the modes for the elimination process. Afterwards, the inverse operation was applied on the phase of the complex form. This operation employs the split-step beam propagation method in order to eliminate the modes during the propagation of the transverse modes. The ‘ipf’ file format were then obtained for the operation to be applied in the waveguide itself. The ‘ipf’ were then applied in the waveguide through the BeamPROP software, this is to eliminate the unwanted modes when the source mode was launched through the waveguide. As the source mode were launched through the waveguide, it will then compute a new set of modes. If the elimination process was a success, it will result in the target modes desired. However, if otherwise, the complex form has to be rechecked and the inverse operation has to be re-applied.

Fig. 1 illustrates the flowchart for the mode conversion process where the modes were computed from the Gaussian beam propagation and from the computed modes, the source mode and the target mode were specified. The process included mode elimination where the unwanted modes were eliminated from the target mode. It uses an inverse function that employs the split step beam propagation method in order to eliminate the modes during the propagation of the transverse modes. The phase of the complex was then converted into its equivalent refractive index representation which is then calculated using the MATLAB software in order to affect the new converted mode. This process tailors the refractive index in a way that it materializes as the phase of the expected mode after the elimination process.

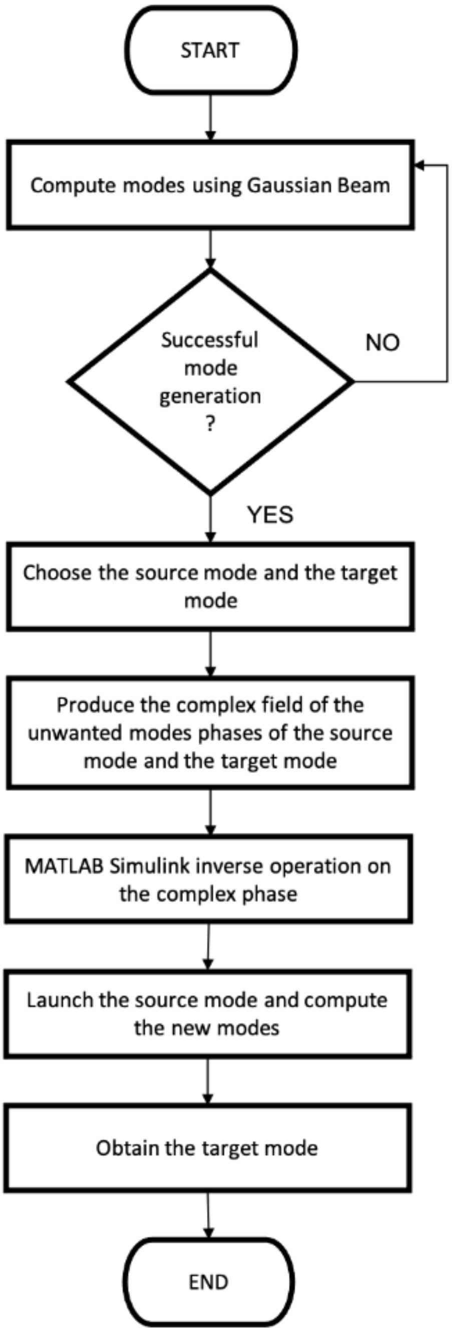


Fig. 1. Flowchart for mode conversion process

4. Simulation

Fig. 2 shows the tapered waveguide designed for this experiment. This specific design was used in order to produce a few-modes fiber. Few-modes fiber was used because the concept of mode division multiplexing is to combine various number of modes into a single fiber, therefore, these specifications allow the modes to propagate through the waveguide successfully.

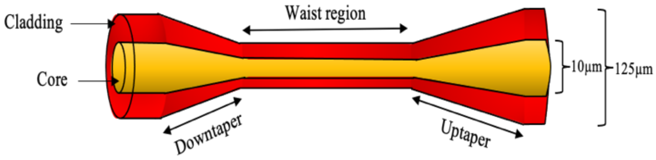


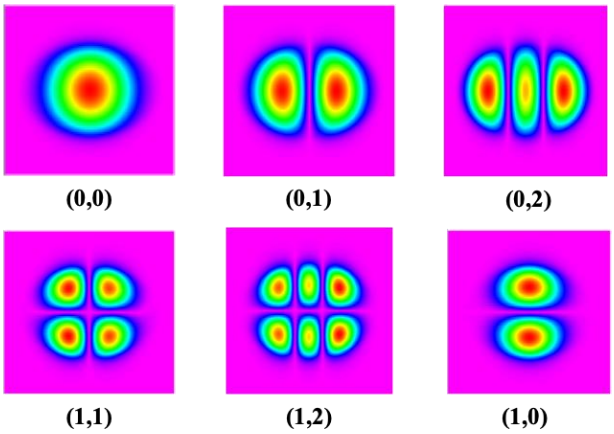
Fig. 2. The tapered waveguide design (color online)

Table 1 shows the parameters used for this design. The total length of the waveguide is about 5000 µm or 0.5 cm. This design is possible since a nanometer size taper was successfully fabricated by Brambilla et al. in 2003 [23].

Table 1. Simulation parameters

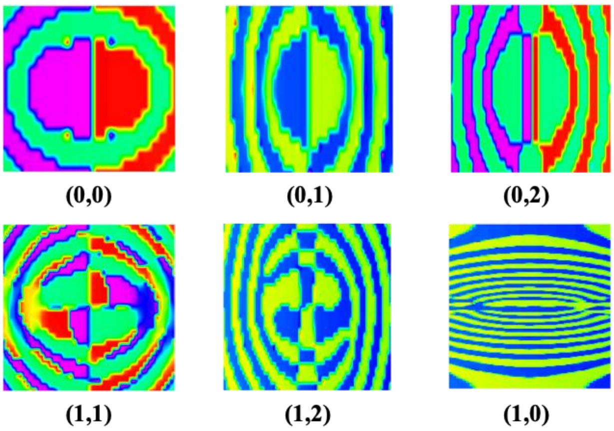
Parameters	Values
Downtaper region length	1515μm
Waist region length	1970μm
Uptaper region length	1515μm
Waist diameter	40μm
Propagation signal wavelength	1550nm
Core refractive index	1.4488
Cladding refractive index	1.4444
Refractive index of the external medium	1
Cladding diameter (untapered region)	125μm
Core diameter (untapered region)	10μm

The modes were computed and were obtained from the designed waveguide. Fig. 3 shows the amplitude of the computed modes where it can be seen that they are compactly shaped which shows that these modes are suitable for data transmission. These modes are known as Hermite-Gaussian (HG) beams as they do not possess a cylindrical symmetry such as LG or Bessel beams [24]. They are often used to represent modes of an optical fiber. HG modes with indices n and m have an M^2 factor of (2n + 1) in the x direction, and (2m +1) in the y direction [25]. Fig. 4 shows the phase of the modes computed coherently.


(0,0) **(0,1)** **(0,2)**

(1,1) **(1,2)** **(1,0)**

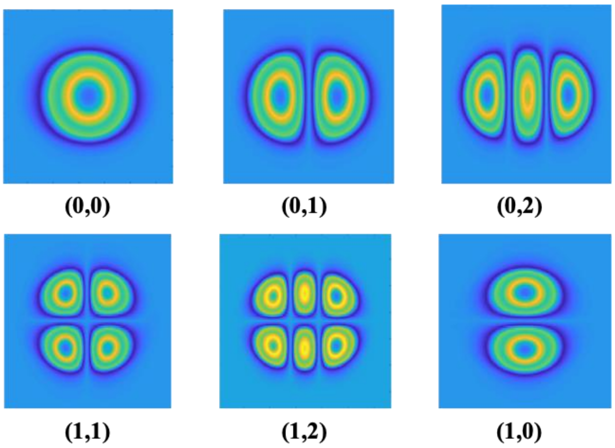
Fig. 3. The amplitude of the computed modes (color online)


(0,0) **(0,1)** **(0,2)**

(1,1) **(1,2)** **(1,0)**

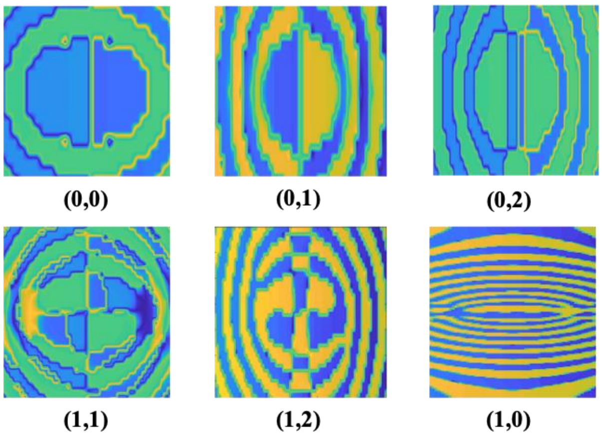
Fig. 4. The phase of the computed modes (color online)

The format of the modes was then switched from a ‘unit8’ which was the original format to a ‘double’. This is to make it possible for the modes to undergo the MATLAB process. Fig. 5 shows the amplitude of the modes while Fig. 6 shows the phase of the modes. From the observation of the phase of the modes, it can be seen that modes (0,0), (0,2), and (1,1) seem to have a darker intensity compared to the others meaning that they retain more optical power and hence perform at optimum when transporting data.


(0,0) **(0,1)** **(0,2)**

(1,1) **(1,2)** **(1,0)**

Fig. 5. The amplitude of the modes in form of ‘double’ (color online)


(0,0) **(0,1)** **(0,2)**

(1,1) **(1,2)** **(1,0)**

Fig. 6. The phase of the modes in form of ‘double’ (color online)

In order to proceed with the conversion process, the source mode and the target mode must first be chosen. In the case of Gaussian Beam to mode conversion, the mode (0,0) is known as the fundamental mode or the Gaussian Beam [23], was chosen to be the source mode. As for the mode to Gaussian Beam conversion, mode (1,0) was used as the source mode, it was chosen at random to become the desired output data in this simulation. The basis for choosing this mode is to test and prove that randomization can be applied to source modes such that any other mode which has enough optical power can be applied just like any other mode. It was also used for the single mode conversion. Mode division multiplexing comes into play when two modes were to be converted into two other modes. For this conversion, mode (1,0) and (3,0) was used. For the three modes conversion, it undergoes mode division multiplexing as well, and the modes chosen for the source were (2,0), (3,0), and (0,0).

Fig. 7 shows the complex form of the modes which needs to be eliminated in order to produce the source mode. This means that when the source mode propagates through the fiber, other unwanted modes will not be produced.

Fig. 8 shows the complex form of the modes which needs to be eliminated in order to obtain the target mode. Once the source mode had propagated through this elimination process, the target modes will be obtained. The whole process was done by combining the unwanted modes and applying Fourier transform which transforms a signal from Time Domain representation to its Frequency Domain representation.

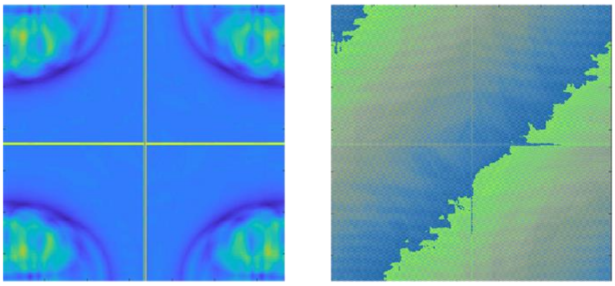

(a) (b)

Fig. 7. The complex form of the source mode.
(a) The amplitude, and (b) the phase (color online)

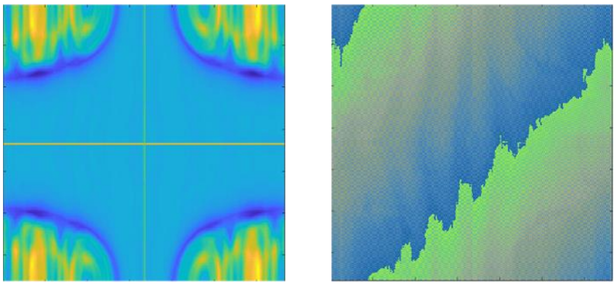

(a) (b)

Fig. 8. The complex form of the target mode.
(a) The amplitude, and (b) the phase (color online)

In Figs. 9 and 10, the phase of the complex form of both the source mode and the target mode, respectively are shown. The original complex phase was inverted in order to counter the formation of the unwanted modes, in other terms, eliminating them. This inverted complex phase had the original format of ‘bmp’ which was then changed to ‘ipf’ file format which is known as the index complex phase for it to be used in the tapered waveguide design is known as the information presentation facility which is a direct numerical representation of the refractive index distribution. This is to specify the waveguide for which the target mode is needed once the source mode had propagated through it. Hence, when the propagation has become successful, the mode conversion has been done.

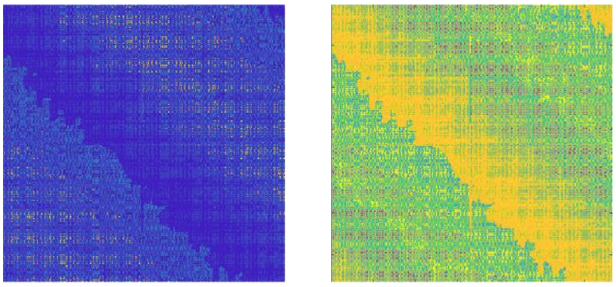

(a) (b)

Fig. 9. The ‘ipf’ (information presentation facility) file format and the index format of the source phase.(a) The inverted format, and (b) the index format (color online)

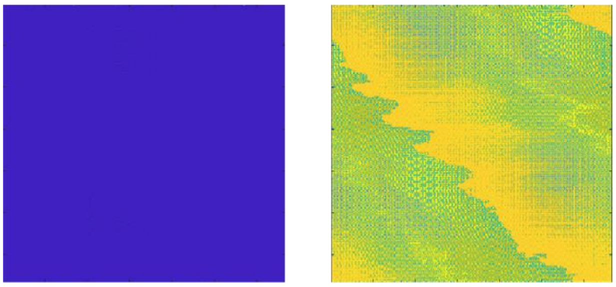

(a) (b)

Fig. 10. The ‘ipf’ file format and the index format of the target phase. (a) The inverted format, and (b) the index format (color online)

5. Results

5.1. Gaussian beam to modes conversion

Fig. 11 shows the conversion of the Gaussian Beam into various modes. The modes produced by the Gaussian Beam are modes (1,0), (0,1), (2,0), (1,1), and (2,1).

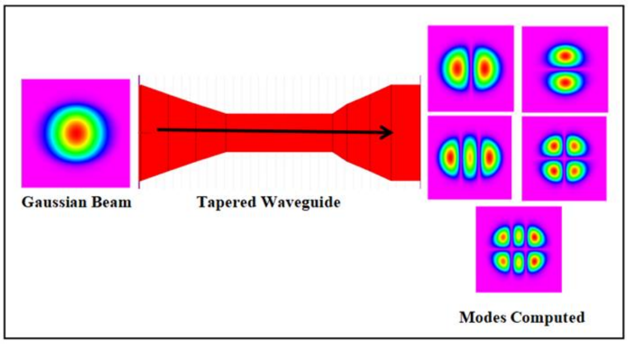


Fig. 11. Gaussian Beam to Modes Conversion (color online)

5.2. Mode to Gaussian beam conversion

Fig. 12 shows the possibility of a specific mode to be converted back into a Gaussian beam. The source mode (1,0) was used to be converted into mode (0,0) which is known as the highest order of mode. Hence, the Gaussian Beam itself.

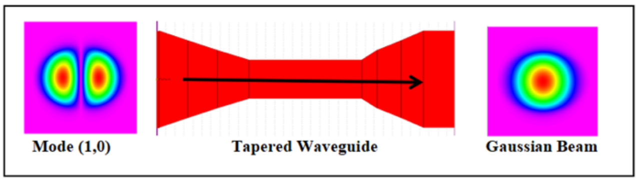


Fig. 12. Mode (1,0) to Gaussian Conversion (color online)

5.3. Single mode conversion

In Fig. 13, the mode (1,0) was again used as the source mode. It was converted into another specific mode which was mode (2,0). This illustrates the ability for the tapered waveguide to convert a specific mode into a target mode by way of changing the refractive and effective indices of the waveguide, thereby telling the system the mode to be reproduced.

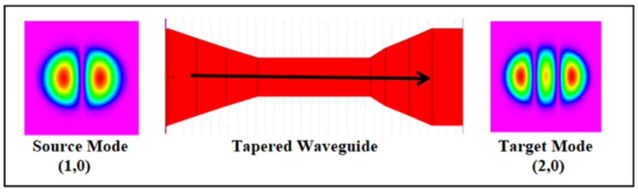


Fig. 13. Mode (1,0) to Mode (2,0) Conversion (color online)

5.4. Two modes conversion

As for the two modes conversion in Fig. 14, the two source modes that have been chosen are modes (1,0) and (3,0). These modes must first undergo the multiplexing process where they were combined into a single fiber. As they propagate through the waveguide, they are converted and demultiplexed into two other modes which are modes (4,0) and (2,0).

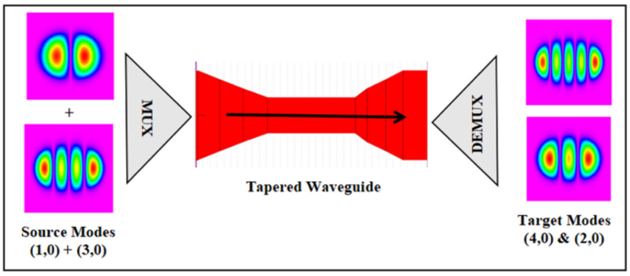


Fig. 14. Modes (1,0) & (3,0) Converted to Modes (4,0) & (2,0) (color online)

5.5. Three modes conversion

In Fig. 15 above, three modes were chosen as the source modes which were modes (2,0), (3,0), and (0,0). They were multiplexed into a single fiber and were propagated through the waveguide. As a result, the modes were converted and demultiplexed into three other modes that were targeted, which are modes (4,0), (1,0), and (0,1).

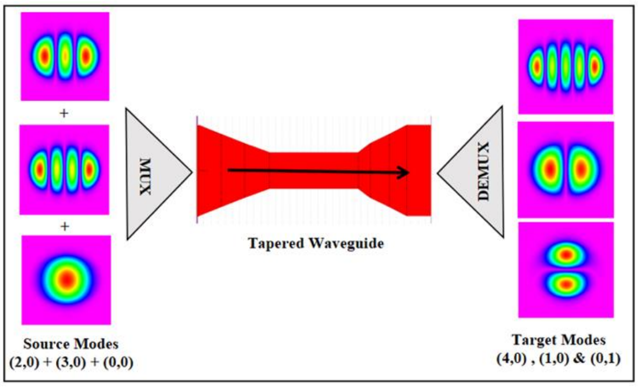


Fig. 15. Modes (2,0), (3,0), & (0,0) Converted to Modes (4,0), (1,0), & (0,1) (color online)

6. Conclusion

In conclusion, it can be said that the tapered waveguide was designed for the purpose of mode conversion with modes computed from this waveguide to be used as the source modes and the target modes. These can be applied in data center switching in order to increase the bandwidth capacity as each mode can be used as a channel to carry data. The first trial was to convert the Gaussian Beam into a mode and vice versa. A specific mode was then chosen to be converted into a different mode. Then, mode division multiplexing was implemented during the process of converting two modes as well as three modes. This paper has showcased that mode division multiplexing in conjunction with mode conversion is a promising technology to create data channels in future applications in data and tele-communications.

Acknowledgements

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