Chapter

Structured Light Fields in Optical Fibers

Monika Bahl

Abstract

Structured light, tailored light, sculpted light, or shaped light is a term used for custom light fields and finds enormous use in literature these days. Some of the history's most brilliant researchers, from Newton to Maxwell to Einstein, have studied the nature of light over the centuries. We believe that we know everything about light, its generation, detection, and applications; yet, it continues to surprise us even today. Indeed, one discovery about light's peculiar behavior has offered a new insight into how light works and rendered some intriguing applications. In 1992, physicists mastered a surprising feat—generating light beams that twist like a helical corkscrew. This phenomenon is called twisted light and has led to an altogether new field of optics, known as singular optics. Today, twisted light is being used to build optical tweezers and ultra-powerful microscopes, and it could eventually be used in microscale machinery and for novel spectroscopic analyses. But perhaps the most important use of this structured light is in optical communications, where it moves through optical fibers. This light has the potential to greatly enhance the bandwidth of data networks and, hence, the speed of data transmission.

Keywords: structured beams, tailored light, optical vortex, orbital angular momentum, optical fibers, data communication

1. Introduction

Light is an electromagnetic wave, composed of electric and magnetic fields. The fields oscillate in a direction perpendicular to the direction in which the wave is moving. If the electric field is always oscillating in the same plane, the light is said to be linearly polarized. Photons of such light possess a linear momentum. Such photons have the power to propel a boat if the solar sails absorb the linear momentum. If the direction of the plane in which the light's electric field is vibrating is itself rotating as the wave moves, light is said to be circularly polarized. In this case, light is said to possess a spin angular momentum. When such a light hits a floating ball, it will start to spin like a planet, rotating about its own axis. We thus had these two types, and surprisingly, it turned out that these are not the only ways light behaves. Allen et al., in 1992, showed in his seminal paper that light may possess another strikingly different characteristic behavior [1]. It happens when the wave fronts, instead of moving in a straight line or diverging/converging, tend to bend, rotate, and propagate in a helical fashion. This was something unexpected and very different from the already known phenomenon. This implied that the energy propagation direction is not a straight line but that too forms a helical trace as the wave moves in the forward direction. Hence, the Poynting vector (S = E × H) changes its direction continuously as the wave moves. Therefore, a given phase front will rotate around the center and trace a helix as it propagates. Such a wave is said to possess a momentum, apart from the linear and spin momentum, which is termed as the orbital angular momentum or OAM. The center of the wave thus carries a singularity of phase called the optical vortex, and the intensity profile represents a doughnut [2–17]. Hitting with this type of light, a free-floating ball will revolve in a circle about a central point as a planet orbits a star. Thus, a "vortex beam" represents a column of light with a hole in the center. In 1991, physicist Robert Spreeuw, at the time a PhD student in Han Woerdman's lab at Leiden University in The Netherlands, sat down during a team coffee break and presented some ideas about how to make twisted light. "The first reactions were a bit doubtful," Spreeuw recollects. "But we kept thinking about it and, bit by bit, it started to look more realistic."

Angular momentum of photons consists of two different components. The first one is the spin angular momentum (SAM), which corresponds to the polarization of the photon. The second component is the orbital angular momentum (OAM), which relates to the spatial phase profile of the photon." Both the components have been used extensively in optical experiments in the laboratories. Moreover, polarization has been used successfully in quantum experiments in free space for about an order of 100 km [18–23]. The polarization of a photon is still more easily controllable and resistant against atmospherical influences and resides in a two-dimensional state space. This places an inherent limit on how much information one can send per photon. An alternate way to encode information is in the OAM, another degree-of-freedom of a photon that offers infinite unbounded number of discrete levels theoretically and is able to render faster effective communication over long distances [18–23].

A brief note on the light-carrying OAM would give an insight into what it looks like. This light has a "twisted" or helical wave front, with an azimuthal phase varying from 0 to 2 πl. The integer l stands for the topological charge or helicity, and $l\hbar$ is the OAM of the photon. In 1992, Woerdman and his colleague Les Allen created twisted light in the lab and showed that even a single photon of light has OAM [1]. In the next year, they showed how to convert a normal helium-neon laser to one that carried OAM. One way to create twisted light is to send it through a phase plate with thickness varying azimuthally. This shapes the wavefonts of the field into a form resembling a helix. It is as if you took a rod and swirled it around to create a vortex in the phases of the electromagnetic waves. This is similar to a vortex in water waves. Topological charge (l) 1 means there is 1 helix propagating clockwise (say) in space, charge 2 means 2 interwined helices propagate, while −1, −2, etc., mean that 1 and 2 helices propagate anticlockwise in space. Higher order charges would increase the number of helices. **Figure 1** shows a plane wave (l = 0) and helical waves with l = 1 and −1, respectively.

Beams carrying OAM can also be generated in the lab using other techniques like a helical mirror or using a computer-generated hologram. Although many of these and other techniques are available, researchers are excited about the potential uses of these beams. Such beams have the potential to trap and rotate particles (optical tweezers), render fast optical communication, used for quantum computing, and use in various other areas. In 1995, an Australian team placed small particles in the dark, central cavity of an OAM laser and watched them whirl around, providing visual proof that the light was carrying OAM. The researchers could even reverse the direction of the OAM laser's twist and spin the particles the opposite way. Thus, an exciting new degree of freedom has been made available to the researchers to extract the potential of these twisted wavefronts. These can be launched into the optical fibers (OF) and photonic crystal fibers (PCF) and provide an all new technique to communicate data at speeds higher than the available ones. But before

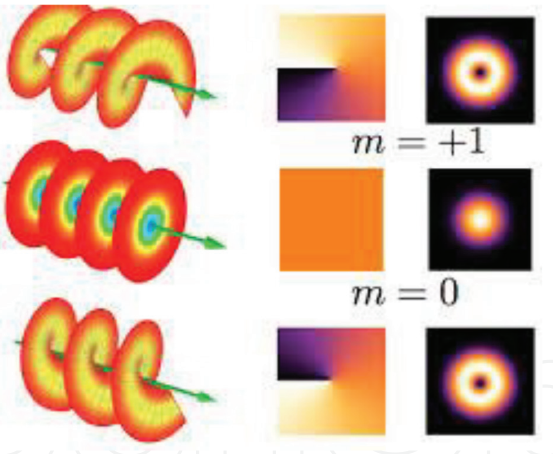

Figure 1.
Phase fronts/wave fronts, phase profiles and transverse intensity profiles of a positive helical wave with m = 1, a plane wave, and a negative helical wave with m = −1. (ref: phot https://futurism.com/new-understanding-twisted-light-affect-use-quantum-computing).

moving further, let me give you a brief description of what optical fibers are and how they are used in data communication.

2. What are optical fibers?

Optical fibers are dielectric wave-guides, circular in shape that can transport optical information and energy. They have a central core that is surrounded by a concentric cladding that has a slightly lower refractive index than that of the core. Optical fibers are normally made of silica doped with index-modifying dopants such as GeO_2 [24–29]. A protective coating of one or two layers of a cushioning material (such as acrylate) is used to reduce cross talk between adjacent fibers and microbending, which occurs when fibers are pressed against rough surfaces. Microbending and cross talk increase the loss of optical energy as the optical beams propagate through the fiber. Fibers are typically incorporated into cables in order to provide environmental protection. Typical cables have a polyethylene sheath that encases the fiber within a strength member such as steel or Kevlar strands. **Figure 2** shows a typical sketch of an optical fiber.

Since the core has a higher index of refraction than the cladding, light will be confined to the core when the condition for total internal reflectance (TIR) is

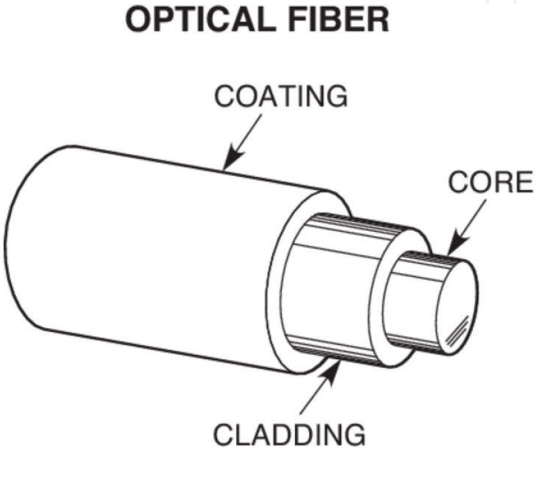

Figure 2.
Cross-section view of an optical fiber (https://www.newport.com/t/fiber-optic-basics).

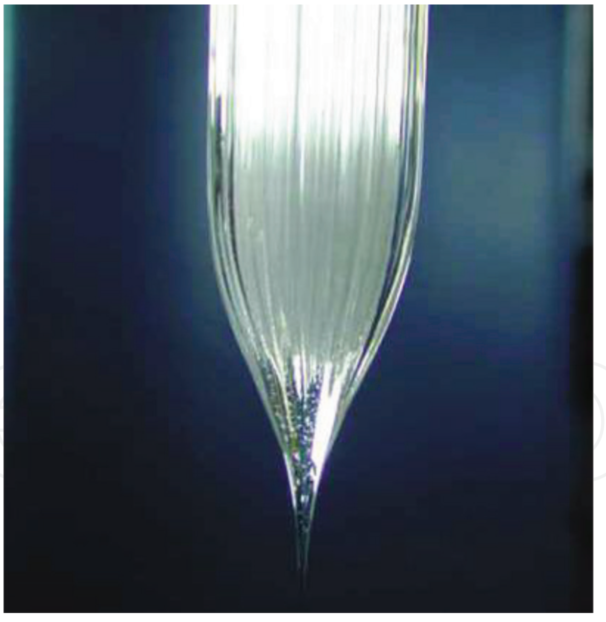

Figure 3.
Close-up view of a fiber preform (https://www.newport.com/t/fiber-optic-basics).

Figure 4.
Fibers can be connected (https://www.newport.com/t/fiber-optic-basics).

met. The composition and geometry of the fiber determine the fiber modes or the discrete set of electromagnetic fields, which can propagate in the fiber (**Figure 3**).

Directly connectorized fibers may furthermore provide beam expansion to lower the fiber end facet intensity and reduce the risk of damage at high power levels (**Figure 4**).

3. Can optical fibers be used for communication and why?

No one desires to have a slow Internet connection! I am sure you agree with me on this. It is very frustrating to have a slow Internet speed when one wants to download something or watch a favorite movie online.

Before the wireless Internet era, there used to be the wired, dial-up Internet. In this type of connection, a phone line was used to connect to the Internet. Several hours were spent only praying for a successful connection. A fast Internet was definitely a luxury during those days.

At that point, broadband connections came in, which totally changed the Internet scene. The rates of 2–10 mbps became normal. Nonetheless, this still utilized great old copper wires as the transmission medium.

Around 10 years back, Internet suppliers started utilizing fiber as a medium to transmit signals. The purpose behind this was that the transmission happened along these lines with minimal losses, giving a lot quicker Internet speeds. In 2014, an exploration aggregate at the Technical University of Denmark (DTU) succeeded to transfer 43 terabits for each second over a solitary optical fiber with only one laser transmitter!

Therefore, what makes this fiber-optic technology lot more adept than copper wires? Let us, therefore, have a look at the two transmission media to get to an answer to this question.

3.1 Copper wire

Electrical pulses are sent through a copper wire in case of wired copper communication. How much of the signal will be retained by the time it reaches its destination is determined by the signal strength. The wire's electromagnetic field is constantly monitored for changes at the destination (for example, the router). The destination registers a "1" (logic high), when the field is strong, i.e., above a certain measurement, say, a, while a "0" (logic low) is registered if it dips below that particular measurement.

3.2 Fiber optic cable

A fiber-optic cable is made from fine hair-like glass fiber, which carries light impulses that are transmitted by an LED or a laser source. Data in optical fiber are transmitted in the form of light (**Figure 5**).

Consider a long and flexible pipe, with its insides perfectly coated with silver halide, such that the inside is all a mirror. It is like a cylindrical mirror from inside. When you flash a source of light (a laser or may be a torch), what do you see at the other end? The light will reach the other end, regardless of whether the pipe is straight, curved, or twisted. Is not it? Yes, it will. This is because light will reflect off the sides of the flexible tube at all angles with almost negligible losses. But mirror tubes would be too bulky to handle. Thus, optical fibers are used to serve the purpose. Optical fibers are such flexible pipes made of glass instead of mirrors. It employs the principle of total internal reflection to transmit light from one to the other end.

Glass is amazingly pure; light can make it through even if it is several miles long. The glass for an optical fiber is drawn into an extremely thin strand, with a thickness comparable to that of a human hair. The glass strand is then coated in two layers of plastic.

3.3 Total internal reflection in fibers

Light rays traveling from a denser medium to a rarer medium speed up at the boundary. This causes the rays to bend when they pass from glass to air at an angle

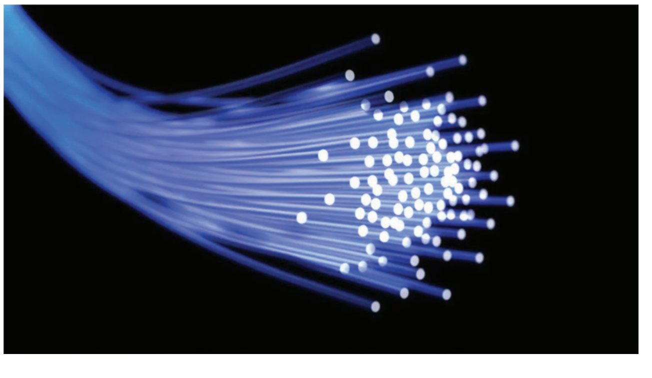

Figure 5.
Light travels in an optical fiber cable (credit: ProMotion/fotolia).

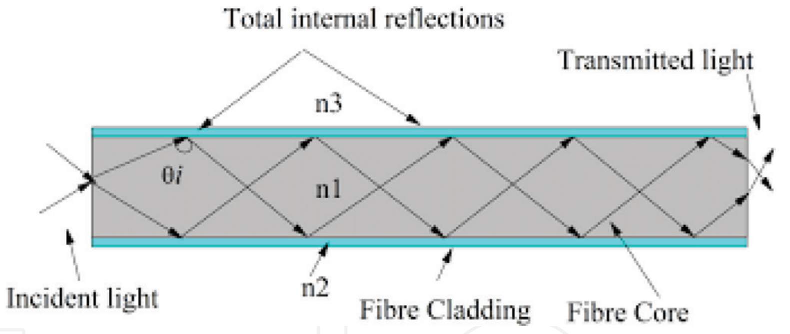

Figure 6.
Total internal reflection in an optical fiber.

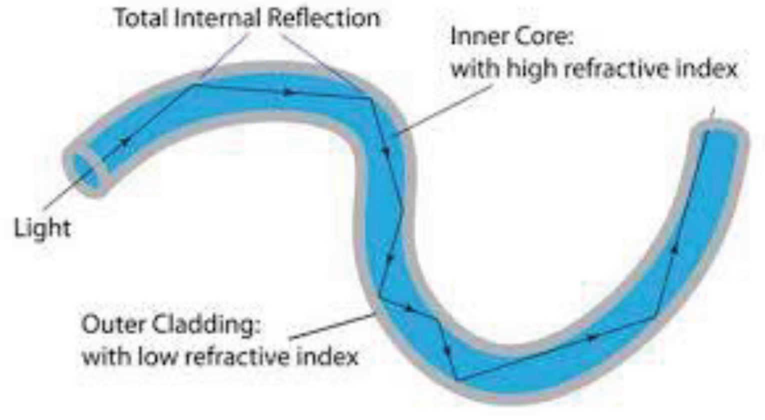

Figure 7.
Light rays undergo total internal reflection inside an optic fiber that is bent.

other than 90°. This is called refraction. The two layers of plastic form the two mediums on which the reflections occur (**Figure 6**).

Beyond a certain angle, called the critical angle, all the waves reflect back into the glass. We say that they are totally internally reflected. The light rays stay inside the optic fiber and are transmitted over long distances with negligible loss (**Figure 7**).

3.4 Benefits of fiber optics

The following properties make fiber optic cable superior to conventional copper cables.

1. Bandwidth

An optical fiber provides more bandwidth as compared to a copper wire and has a standardized performance up to 10 Gbps and beyond, something that it is impossible to achieve with a copper wire. A higher bandwidth means that the fiber can carry more information with far greater efficiency than a copper wire.

2. Range of transmission

Data travel in the form of light through a fiber optic cable. The loss of quality of signal is almost negligible in the case of total internal reflections within the glass fiber, and hence, very little signal loss occurs during transmission. Data can, thus, move at higher speeds and for greater distances.

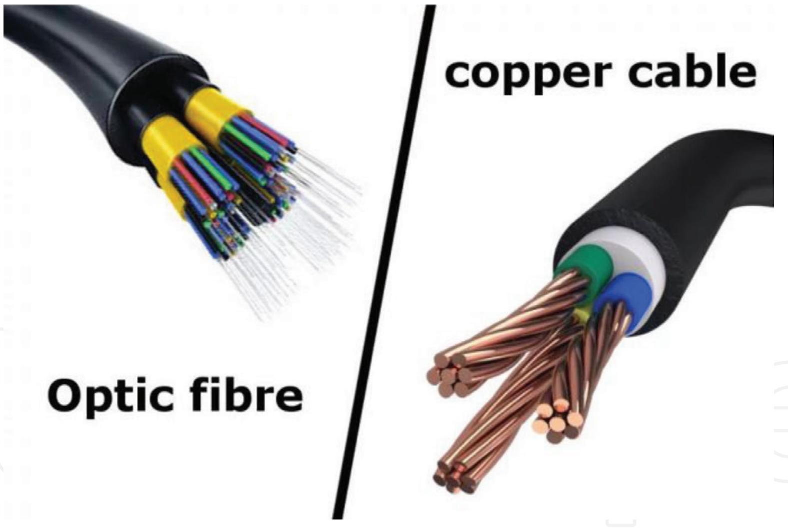

Figure 8.
Optic fiber is much lighter and thinner compared to the conventional copper cable.

3. Not susceptible to interference

Data transmitted through a fiber-optic cable is much less susceptible to noise. It is also less susceptible to electromagnetic interference as compared to one moving through a copper wire. For example, there would be almost zero degree of quality degradation in a signal through a fiber optic cable, say even for a distance of over two kilometers, while a signal transmitted through a copper wire would experience a great deal of degradation in quality. It is, therefore, so efficient that roughly 99.6% of the signal reaches the router in most cases.

4. Size, weight, and strength

A copper cable is bulky and heavy as compared to a fiber optic cable that is much lighter and thinner. It can be used very efficiently in underground pipes that are confined to the ground and are also much stronger, with eight times the pulling tension of a copper wire. It is also tough against environmental factors and atmospheric distortions and hard to damage or kink (**Figure 8**).

5. Cost

The initial cost of material and installation of an optical fiber is high as compared to a copper wire, but in the long run, the working cost is much less. Moreover, a fiber network has a low maintenance cost and requires very few networking hardware.

6. Durability

Fiber optic cable is highly resistant to many environmental factors that, otherwise, affect a copper cable network. No electric current can flow through the former as the core is made up of glass which is a perfect insulator. Fiber cables can be made to run next to any industrial equipment too. An optical fiber is also more resistant to temperature fluctuations as compared to copper and can also be submerged in water.

As discussed, optical fibers can communicate data through transmission of waves based on the phenomenon of total internal reflection. The theoretical bandwidth of optical fiber transmission is of the order of few terabits.

Bandwidth can be enhanced by employing two techniques. The first one is known as the time division multiplexing (TDM). Multiple channels are transmitted

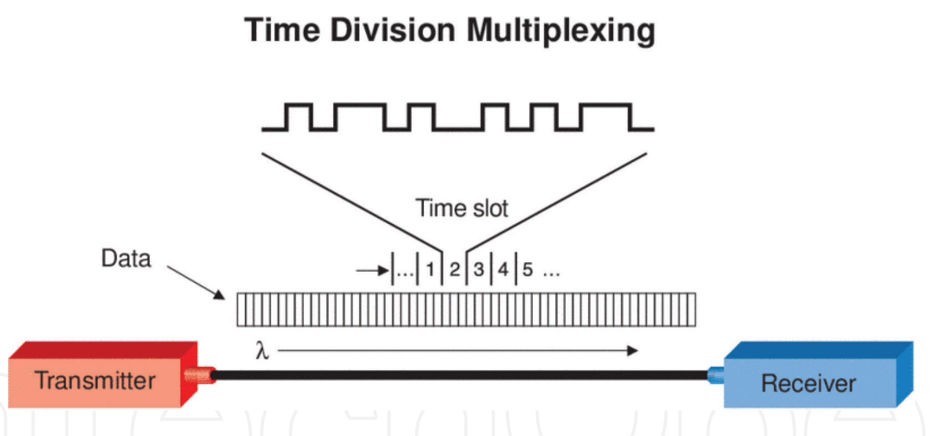

Figure 9.
Time division multiplexing (https://www.newport.com/t/fiber-optic-basics).

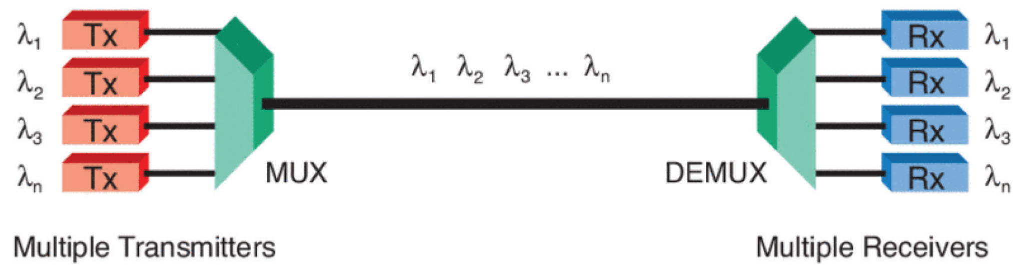

Figure 10.
Wavelength division multiplexing (https://www.newport.com/t/fiber-optic-basics).

onto a single carrier by increasing the modulation rate, and each channel is allotted a time slot (**Figure 9**).

The second method is known as wavelength division multiplexing or WDM. Using this method, capacity can be increased by using more than one optical carrier (wavelength) in a single fiber. Therefore, adding a second transmitter and receiver to an optical fiber can double the bandwidth of that communications system (**Figure 10**).

As per the data on the Newport website, the ITU (International Telecommunication Union) had proposed a set of closely spaced wavelengths in the 1550 nm window. This method of WDM is known as Dense Wavelength Division Multiplexing or DWDM. These different wavelengths or channels, spaced 100 GHz apart or 0.8 nm approximately, form the ITU-T grid. The 1550 nm window has the smallest amount of attenuation and lies in the band in which erbium-doped optical amplifiers operate. DWDM systems have a fixed starting and a distinct ending point. Thus, these are, therefore, called point-to-point links. Research is being done to make these networks evolve into completely configurable networks that are not limited to fixed point-to-point links.

Transparency in the optical layer opens many possibilities for the future. Digital and analog transmission can occur on the same fiber. Different bit rates using different protocols will all travel together. Current research is being performed on reconfiguring an optical network in real time. Wavelength selective switching allows wavelengths to be routed through the network individually. Some of the applications of this are for network restoration and redundancy, which may reduce or entirely eliminate the need for an entire back up system to help the network recover from failures such as equipment malfunctions or fiber breaks. A reconfigurable network may offer bandwidth on demand to configure itself to optimize for traffic bottlenecks. The future may also include wavelength translation to convert traffic on one wavelength to another wavelength in the optical domain.

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All optical switching is still in the research phase; however, researchers are looking for ways to create reliable, low loss switches with fast switching speeds. Investigation into the possibility of optical packet switching and other novel technologies is currently underway. The all-optical network may be just around the corner.

The future is fiber-optic technology, and the network is growing exponentially worldwide. Most major companies are already using fiber-optic systems in their backbone applications. These systems offer higher reliability and speed.

4. Can structured beams propagate in optical fibers?

4.1 Yes… twisted light through the light pipe…

Today's optical-fiber communication systems use wavelength division multiplexing, as discussed in Section 2, to squeeze multiple channels of data through the same fiber simultaneously, offering much speedier data transfer rates.

But there is another breakthrough research in squeezing photons into this light pipe! It is the "twisted light" or the photons with an orbital angular momentum (OAM) that can also be utilized to encode data channels. It is like another degree of freedom or another dimension on which data can be transferred. The angular momentum has an infinite number of states. Each wavelength can carry different values of this angular momentum. Thus, OAM appears to be one more parameter of light that was not explored till date for communications (**Figure 11**).

Researcher Miles Padgett and his coworkers in the University of Glasgow discovered in 2004 that OAM modes can be sent through air. They used a holographic

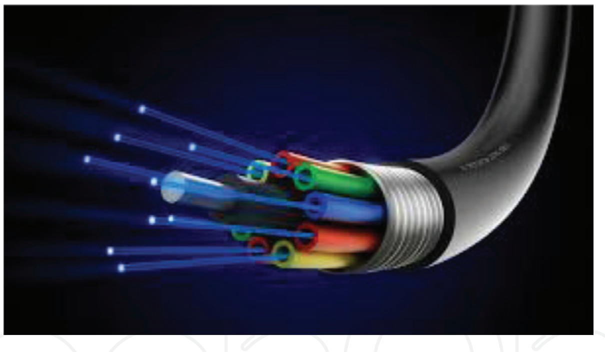

Figure 11.
Twisted light through an optical fiber (https://goo.gl/images/vAZD3C).

Figure 12.
Light trails (https://www.creativity103.com/collections/Lightwaves/slides/twisted_light_loops.html).

Figure 13.
Wireless communication through twisted light (https://www.rdmag.com/news/2017/10/twisted-light-could-illuminate-new-path-wireless-communications).

pattern to split a twisted laser light into nine separate helical beams and sent them 15 m through the air to a telescope. At the receiving end, this telescope was able to distinguish and read out all the beams simultaneously. The bandwidth of the experiment was not quite high though. A multiplexer and demultiplexer for such twisted or helical beams were presented in a research paper at the Optical Fiber Communication Conference and Exposition, in Los Angeles, in March. The multiplexing device presented in the conference was one with multiple waveguides that were carved onto a single chip. Later, Willner et al., researchers from the University of Southern California, reported a research work related to transfer of data using OAM modes of light in Nature Photonics in 2012. They had used twisted light to transfer data at approx. 2.5 terabits per second over a distance of about 1 m. But twisted beams would need to travel lot farther in order to be used for optical communications. Later, a team in Vienna, in 2014, set a record by sending pixelated images of few famous Austrians by using twisted light. The images were sent to another site in Vienna that was 3 km apart. The researchers used helical beams with four helices or twists, such that a data transfer rate of 4 pixels per second could be achieved (**Figures 12** and **13**).

The improvements should be welcome news to companies such as Intel and Luxtera, which have been racing to find ways to replace the expensive exotic semiconductors and separate components in most optical communications systems with cheap integrated chips made of silicon. Twisted light arrays could allow communication channels between chips in a computer.

5. Conclusion

Twisted light beams carrying an orbital angular momentum (OAM) have since been used to build optical tweezers, which use laser light to trap microscopic particles and control their movements. Instead of merely pushing or pulling at the particles, an OAM laser works like a tiny wrench that can torque objects around. In recent years, engineers have built ever smaller OAM beams—some barely as wide as a human blood cell—in the hopes of using them to drive microscale gears and even nanotech machiner. Biomedical diagnostic devices built on a single silicon chip could use such twisted light to operate microscopic equipment or detect the flow and viscosity of minuscule amounts of liquids. Because twisted light is so unusual, it can excite atoms and molecules into odd states not often seen in nature. Electrical engineer Natalia Litchinitser of the University at Buffalo in New York and her colleagues have used metamaterials—synthetic composites that exhibit properties not found in natural materials—to squeeze an OAM beam so that it is only a few nanometers

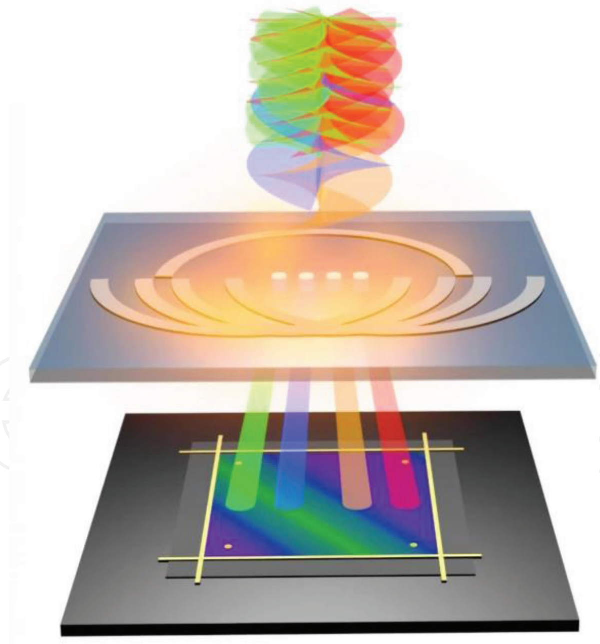

Figure 14.
The miniature OAM nano-electronic detector decodes twisted light (image courtesy: RMIT University).

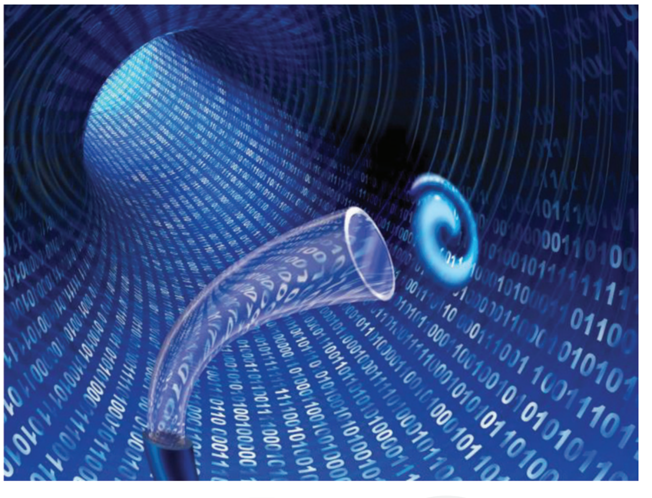

Figure 15.
Twisted light sending data through an optical fiber (https://spectrum.ieee.org/tech-talk/semiconductors/design/twisted-light-sends-data-through-optical-fiber-for-first-time).

wide. Using such beams, they hope to stimulate atoms and molecules into energy states that are extremely difficult to achieve naturally. When the molecules fall back to their ground states, they release characteristic flashes of light, which Litchinitser says could be useful in new kinds of spectroscopic analysis, for instance teasing out the individual components of complex compounds (**Figure 14**).

But perhaps the biggest application of twisted light is optical communications. Recently, physicists have shown that photons are not the only ones with OAM. Pushin et al. have demonstrated that neutrons, which according to quantum mechanics act as both particles and waves, can be converted to possess OAM modes. Even acoustic waves have been induced into OAM modes, allowing them to carry more information. Some researchers have also suggested that sound waves carrying OAM can be used for underwater communication networks. These waves would travel better in water, where light is quickly absorbed otherwise (**Figure 15**).

Using twisted optical beams, one would be able to use Internet at 100 times the current speed. The growing potential of OAM beams has astounded those who work with them and surprised those who first imagined their possibility. "At one time it was just a fun idea," says Spreeuw. "I could never suspect it would grow into such an industry."

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