All Optical Solution for Free Space Optics
Point to Point Links

Daigo Hirayama and Banmali Rawat*

Department of Electrical and Biomedical Engineering
University of Nevada, Reno, NV 89557, U.S.A.
E-mail: rawat@ee.unr.edu

Abstract – The focus of this paper is to eliminate the electrical devices for FSO point to point links by replacing them with optical devices. The concept is similar to an extended beam connector. The aim is to achieve a detectable signal of 1nW at a distance of 500 meters at a wavelength of 1500-1600nm. This leads to application in building to building links and mobile networks. The research examines the design of the system in terms of generating the wave, the properties of the fiber feeding the wave, and the power necessary to achieve a usable distance. The simulation is executed in Code V by Synopsys, which is an industry standard to analyze optical systems.

Index Terms: Fiber Optics, Communications, Axicons, Free Space Optics, Bessel and Code V.

I. INTRODUCTION

Free Space Optics (FSO) provides a hybrid optical solution in point to point Local Area Network (LAN) links. FSO systems are highly preferred when electromagnetic interference is high in a particular region and traditional fiber optics link are too costly. FSO systems may also be useful where the link is temporary or mobile. The amount of conversions needed for a FSO link diminishes its effectiveness. Information travels down the optical LAN backbone to the FSO system. The FSO system’s laser emits an optical beam across the atmosphere to a detector which feeds the signal to the other end user. This system requires four conversions. The optical LAN must convert the signal to an electrical signal to modulate the laser. The laser then converts the electrical signal to an optical signal. On the detector side, the photo detector reverses the process. By removing the conversions and replacing the components with optical devices, system delays are reduced, high fidelity is achieved and overall cost may be reduced through the decrease of power consumption and materials. Furthermore, electrical devices must be phased out of networks to achieve all the benefits of optical devices throughout the entire network. Therefore, this research proposes a new way of establishing point to point FSO links using only optical devices.

This paper proves that replacing all the electrical devices with optical devices is possible and feasible through a lens system. The concept is similar to an extended beam connector. However, where an extended beam connector deals with a gap of a few millimeters, this FSO link covers a distance from 100 meters to one kilometer. This distance covers the normal range needed to establish useful point to point links in a FSO LAN. The aim is to achieve a detectable signal of 1nW at a distance of 500 meters at a wavelength of 1500-1600nm. With 1nW at the edge of the receiving fiber, the signal should be strong enough to flow through the receiving LAN despite any attenuation. Wavelengths of 1500-1600nm are commonly used in fiber optics systems, are subject to less atmospheric noise and due to Erbium Doped Fiber Amplifier (EDFA) being used in optical systems [1].
II. BASIC THEORY AND ANALYSIS

A complete optical FSO point to point link provides an alternative to the conventional FSO point to point link. A complete optical system provides better bandwidth and fidelity to the signal. It reduces the delay caused by the modulation and demodulation of a signal. Furthermore, the system’s dimension and cost makes it ideally suited for mobile networks. The simplicity of the device increases the reliability. There is neither moving pieces to break nor any electronics that would be damaged due to adverse weather conditions. The designed optical FSO point to point link does not have any mechanism to prevent pointing loss due to unwanted movements of the platform. In order to prevent excess pointing loss, the distance between the point to point systems should stay around 100m to 500m. This distance is used commonly in inter-building communication and serves campus locations and mobile networks well.

A. Intensity Analysis

The largest obstacle is in transmitting the beam across the atmosphere. Gaussian beams suffer from dispersion and diffraction, limiting the range of the system. The standard way of overcoming this problem is to boost the power of the signal or to reduce the beam divergence to a few milli-radians. The Bessel beam is able to overcome the problem of diffraction. Dispersion may still exist because the beam generated is not a true Bessel beam, but a Bessel/Gaussian hybrid. As long as R, the radius of the axicon, is larger than the full wave half maximum (FWHM) of the generated pulse, the Bessel beam always outperforms the Gaussian beam. The normalized intensity from the axicon is obtained by taking the square of the Huygens Fresnel equation in cylindrical coordinates as [2]:

\[ I(r,z) = \left( \frac{k}{z} \right)^2 \left| \int_0^\rho r e^{i\frac{kr}{z}} \right|^2 \left( I_n \left( \frac{kr}{z} \right) \right) dr \]  \hspace{1cm} (1)

where

\[ k = \frac{2\pi}{\lambda} \]

\[ r^* = \text{transverse distance to the optical axis } z \text{ (for on axis intensity, this is equal to } 0) \]

\[ r = \text{radius of the feeding beam} \]

\[ J_0 = 0^\text{th order Bessel Function} \]

\[ (r^*, z) = \text{arbitrary point in the direction of propagation} \]

\[ \rho = \text{radius of aperture} \]

\[ \rho_a = 0 \text{ (in this case) or inner radius of an annular lens} \]

The system is concerned primarily with the on-axis intensity, as this part carries the signal. When this intensity is evaluated on the axis of propagation the equation is simplified as:

\[ I(0,z) = \left( \frac{k}{z} \right)^2 \left| \int_{\rho_a}^\rho r e^{i\frac{kr^*}{z}} \right|^2 \]  \hspace{1cm} (2)

The cross section of the intensity can be calculated by combining the Bessel Equation and the Gaussian equation. This equation is a combination of a pure Bessel function and the equation for a Gaussian pulse. The cross section intensity is given by:

\[ I(r) = J_0(\alpha r)e^{-\frac{r^2}{2\sigma^2}} \]  \hspace{1cm} (3)

As the radial wave vector is equal to the radius of the beam formed by the collimating lens, this can be used to relate the NA of the fiber to the collimated beam generating the Bessel beam. The radial wave vector can be related to the numerical aperture by:

\[ \alpha = \frac{f}{\sqrt{\left(\frac{1}{\text{NA}*\pi}\right)^2 - 1}} \]  \hspace{1cm} (4)

This equation gives insight to the output and the acceptance angle of the fiber, which defines the initial parameters from which to start designing the axicon.

B. Collimating Lens Analysis.

The collimating lens ensures that the rays hit the axicon parallel to each other. Without this condition, the phase function would not refract
the rays at the proper angle. The collimating lens has a pretty straightforward design. The effective focal length (EFL), can be found from the radius of the axicon and the numerical aperture as [3]:

\[
EFL \approx \frac{R}{2 * NA}
\]  

(5)

where

\( R = \) radius of the axicon

\( NA = \) numerical aperture of the fiber

The focal length of the collimating lens defines the distance from the fiber to the lens. The proper placement of the fiber generates a plane wave. Code V uses the following formula to express aspheric lenses [4].

\[
z = \frac{cy^2}{1 + \sqrt{1 - (1 - e^2)c^2y^2}} + a_4y^4 + a_6y^4 + \ldots
\]

(6)

This formula normally is solved through linear programming. In this research, the optimization program in Code V provides the solution for this equation, adjusting the lens so that the divergence angle from the collimating lens becomes almost zero [4]. Code V is an optical design and analysis program developed by Synopsys Inc. [4]. The Optical Telecommunication system industry has been using Code V to design and simulate isolators, couplers, wavelength-division multiplex filters and other optical devices. Code V provides optimization and analysis capabilities for an extremely broad range of lenses and optical surface types. This software includes numerous analysis tools which simulate the propagation of light at a wide spectrum of frequencies and presents the output in graphical format or detailed text. The software is ideal for this research because of its analytical tools and its common use in the industry.

C. Axicon Analysis

As discussed earlier, there are various shapes and designs for axicons. Each has their own advantages and disadvantages. The logarithmic axicon gives a more uniform intensity over a given range. The linear axicon provides four distinct advantages. First, the linear axicon provides more power at the desired distance. The design of the axicon is less complex, which decreases the cost of the axicon. Lastly, the simple design allows multiple ways to design and to simulate the axicon.

In order to extend the beam at large distances, the axicon angle must be very small. To achieve a longer range, it would be desirable for the depth of focus region to start away from the axicon. The traditional cone axicon’s phase function is defined when \( d_1 \) equals zero. Thus the traditional axicon does not provide the distance necessary to form the FSO link. This means that an axicon must be approximated using a diffractive or GRIN profile. While the diffractive axicon uses either a conic lens or diffractive gratings to approximate the phase function, the GRIN axicon varies the refractive index of the material to map the phase function. Either design begins by defining the phase function. This phase function dictates the maximum range for the system. Additionally, the angle dictates the location where maximum intensity is obtained. The phase function for a linear axicon is given by [5]:

\[
\varphi^+(r) = -\frac{[1 + a]r^2 + d_2^2}{{1 + a}}^{1/2}
\]

(7)

Where

\( r = \) any point \( r \) along the radius of the axicon

\( d_1 = \) the beginning distance of the depth of focus

\( a = \) a variable defined by the following equation as [5]:

\[
a = \frac{2\pi P_0}{c} = \frac{d_1 - d_2}{R^2}
\]

(8)

Where

\( d_2 = \) the end distance of the depth of focus

\( c = \) estimated slope of the power of the axicon

\( R = \) the radius of the axicon

Keeping the initial power and the average power per unit length as constants, the following relationship is obtained.
This gives a more useful equation for determining the range of the Bessel Beam in terms of the original power, the radius of the axicon and the final power at the end of the depth of focus region as:

\[
(d_2 - d_1) = \frac{\pi P_o R^2}{P_2}
\]

The definition of the depth of focus region provides the basis for the design of the axicon. Theoretically, this distance can extend several kilometers depending on the input power and the detectable power. For practical purposes, this value remains around 100-400 meters. The hyperbolic lens provides a simpler yet just as efficient design and could be readily integrated into Code V. Code V models the hyperbolic axicon with the following equation when \(K<-1\):

\[
y(x) = \sqrt{2Rx + (K+1)x^2}
\]

Where
- \(R\) = Radius of the lens
- \(K\) = conic constant

The conic equation looks very similar to the phase function given by Equation (7). By setting \(R\) equal to 0, the approximation below works well for modeling the axicon:

\[
K \propto -a
\]

This formula results in a diffractive axicon with a circular grating. This combination acts similar to the annular lens. In the case of a linear axicon, two terms in the series provide the best match for the phase function.

**III. SIMULATION METHOD**

Once the lens designs are transformed into the Code V format, the data can be entered in to the Lens Data Manager (LDM). This interface allows the user to define the radius and position of the lenses. In this research, the object represents the end of the fiber and the image represents the detector. Code V does not have a way to easily measure the intensity along the axis of propagation, so the image surface must be moved along the axis and the data recorded at each point. The surface properties option in the LDM specifies the diffraction grating or the phase function of the lens. The numerical aperture and pulse type can be set here to best simulate the optical communication system. Code V has numerous optimization tools. These functions create an aspheric lens or other lens shapes that have a near perfect focus at the image distance or other user defined area. These optimization functions could not be used for the axicon, since the lens needs to focus over a distance rather than just at one point. The output of the optical system is simulated by the Code V Beam Synthesis Propagation (BSP) tool. BSP uses a highly accurate beamlet-based diffraction propagation algorithm in order to measure the intensity of a light source at the image location [6]. BSP’s primary output is a color raster chart that displays the image of the beam perpendicular to the axis of propagation over a specified area or optimized area. BSP also produces text results that give more specific information on the beam propagation and power.

**IV. RESULTS**

![Figure 1: The axial intensity vs. the density for different values of the axicon radius.](image)

(a) I(0,z) R = 0.04 m  (b) I2(0,z) R = 0.03m  
(c) I3(0,z) R = 0.02m
A. Analytical Results

Based on the analytical procedure previously discussed, the analytical results have been obtained. Figure 1 shows the relationship between axial intensity and distance. It is observed that as the beam propagates along the z axis, different phase components of the beam leaving the axicon interfere with each other constructively and destructively, leading to the oscillation seen as the intensity rises linearly. The design of the axicon phase function dictates where the depth of the focus lies. The system is found to be most effective when the desired distance falls in the middle of the depth of focus range. The steep decrease in intensity is expected for a Bessel beam. The Bessel beam properties only pertain to the depth of focus region, beyond that the different phase components no longer intersect. As seen by the green line on Figure 1(c), a small radius results in a beam that does not deliver sufficient intensity to the target area of 150m to 400m. The depth of focus manifests itself as the max of each plot before the intensity begins to drop rapidly toward zero. The larger the radius the longer the range and the more power arrives at the desired point. This is shown by the red line on Figure 1(a). This is in agreement with the Rayleigh range formula. This increase in intensity occurs without an increase in the input power of the system. Changes in the wavelength require a redesign of the phase function in order to properly align the phase components.

As the numerical aperture becomes larger and travels through the two lenses, the Bessel beam grows narrower. As the numerical aperture shrinks the central beam becomes wider and approaches a Gaussian beam shape due to the collimating lens effects. As the numerical aperture becomes larger the beam gets focused instead of collimated. And as it becomes smaller, both lenses have a lesser effect on the beam causing the Gaussian shape to remain. The rings of the Bessel Beam move closer and closer to each other because the Bessel Beam is more focused. Each ring gets thinner and eventually the system looks like a very sharp, focused beam.

Figure 2 shows the effect of changing the refractive index of the axicon on the radial wave vector of the Bessel Beam. A larger radial wave vector means the full width half maximum (FWHM) of the Bessel beam becomes more compressed. As calculated from Equation (4), the graph shows that a larger refractive index corresponds to a large radial wave vector and thus a narrower Bessel Beam. However, the greater focus comes at a price. A greater difference in the refractive index increases the reflectivity of the system which results in greater connector return loss. Thus, a trade off must be made between the FWHM of the beam versus the power lost due to reflected beams.

B. Simulation Results.

The system consists of a collimating lens and axicon to produce the Bessel beam. The software Code V 10.4 from Synopsys is selected to simulate the propagation of the system. This simulation uses a fiber with a numerical aperture of 0.37 and a core diameter of 200 µm. These fiber dimensions were chosen because it is commonly used in local area networks. Many local area networks use Cisco network devices to establish the network backbone. These fiber dimensions fit the standard Cisco point to point link between routers and thus fit the optic point to point link well.
Figure 3. Intensity on the plane of a Bessel Beam generated by axicon, $\rho = 0.04 \text{ mm}$ and $z = 300 \text{ m}$.

Figure 3 shows the Bessel Beam generated by the hyperbolic axicon. It is observed that Figure 3 has significant deformation in the outer rings caused due to hyperbolic lens. Due to the approximation, the lens curves more toward the outside. A smaller axicon radius produces an exaggerated version of this effect. The smaller lens means the aberration occur on the inner rings versus the outer rings. Thus the center airy disk of the Bessel beam forms, but the outer disks compress together creating the larger intensity. A lens with a larger radius also forms a better Bessel beam. However, the aberrations may be used to project more power onto the detector over a short distance, since the system is less stable over a longer range.

In the actual design, a focal length less than the effective focal length prove more useful. This creates a slightly smaller beam that does not go through the edges of the axicon where the shape of the lens deviates from the phase function. As shown in Figure 4, the simulation results follows the curve of the axicon, however, the results do not have a long range and the oscillations are less regular. The simulation also shows that it provides more power for shorter ranges than the theoretically calculated values. The maximum intensity occurs roughly close to theoretical calculations obtained at a distance of about 300m.

Figure 4: Normalized intensity for axicon of radius = 0.04m (a) Simulation (b) Theoretical

A reason for the discrepancy is the difficulty of fitting the phase function to the specifications of the simulation software. The Taylor and conic approximations only work for lens sizes of less than .05m. After that distance, the approximations diverge too far from the phase function to be useful. Even within, the .05m range, the approximations are not perfect fits. This explains the outer rings tendency to blur into each other as shown in Figure 3.

Figure 5 displays the power curve of axicons with different radii. The simulation results do show that the range of the system increases with the radius of the axicon. When the radius doubles, the range also doubles in value. This is in line with the numerical results. While the
range increases, the input power remains the same. However only increasing the radius is not sufficient in extending the range as shown in Figure 5. It is clear that simply scaling the axicon does not produce the desired results. As the radius increases, the conic constant and the phase function change. The axicon needs to be redesigned for larger radii. However, the range of the axicon is clearly affected by its radius. This is expected since the phase function is dependent on the radius as well as the integral that determines the intensity. Theoretically, as long as the radius increases the range of the device also increases. Practically, this is limited by the ability to create the lens. At very large distances, the phase or conic functions would require unattainable accuracy.

Figure 5 also shows that the power generated from the axicon can be more stable if the power is taken over a larger area rather than at a point. The center airy disk of the axicon maintains a radius of less than 15mm past 500m. With a focusing lens of greater than the airy disk, the oscillations have little effect on the power delivered to the receiver. The intersection of the two curves shows the distance at which the systems need to be replaced. As expected when the input power is raised the power at the detector rises as seen in Figure 6. This causes the increase in the effectiveness of the Bessel’s beam. The measured distance starts at 100m because before that distance, the Bessel Beam is still not fully formed and the width of the beam varies greatly. Throughout the depth of focus region, 150m to 400m, the full width half maximum (FWHM) of the beam stays fairly consistent. This demonstrates that while the central air disk contains less power over a short range, the beam delivers more power over long distances. The drop of in the intensity seen in Figure 4(a) is not only attributed to a drop of power, the FWHM of the beam begins to expand after the distance exceeds the depth of focus region. This causes the intensity at the detector to drop rapidly. The width of the FWHM can be decreased by increasing the refractive index of the material or changing the numerical aperture of the input fiber, but this decreases the power delivered to the target area.

Figure 5: Power curves for axicons with (a) radius = 0.02 m and (b) radius = 0.04 m.

![Figure 5](image)

Figure 6: Input power vs. power at detector at peak distance.

![Figure 6](image)
Figure 7: Intensity of Bessel beam versus Displacement at slice centers at (a) numerical aperture=0.21 (b) numerical aperture=0.60

Figure 7 shows the numerical aperture for various cross sections of the pulse. It is observed that the pulse cross-section changes with the numerical aperture. Figure 7 (a) shows significant deformation in the Bessel beam. The beam resembles a 1\textsuperscript{st} order Bessel beam, but this is not due to the lens creating a 1\textsuperscript{st} order Bessel beam. The beam seen in Figure 7 (a) is a similar to a Gaussian beam. The dip at the maximum occurs because of the center of the axicon. The central spot of the axicon is a source of deformation. The center behaves much like the annular lens center. This means that most of the light is reflected back or refracts away from the axis of propagation. This can be seen clearly when the numerical aperture of the system is less than 0.21. The large dip in the intensity profile was caused by the beam forming around the center of the axicon. As the numerical aperture grows, the beam is wide enough that the outer portions of the beam converge to begin forming the center. As the NA becomes larger and larger, a plane wave is formed before the collimating lens. This causes the collimating lens to do the opposite of its intended purpose and focuses the light instead as shown in Figure 7(b). Recall that a lens that creates an image at infinity generates an image at its focal length when the object is at infinity. Thus a Bessel beam is not formed when the numerical aperture is very large as observed in Figure 7(b).

Figure 8 shows the changes in the Bessel beam profile as a function of the wavelength of the system. It is observed that the wavelength of the design can vary between ±20nm and still retains its ability to project power. The phase function needs to be designed at a certain wavelength. This determines the angle at which the different phase components combine to form the depth of focus region. Figure 8(b) and (c), show the profile of the Bessel beam as the wavelength falls above the tolerance of the axicon design. Both of these figures show a well-defined Bessel beam in the center. However in Figure 8(b), the outer aberrations have become larger and the rings have narrowed. In Figure 8 (a), central airy disk is no longer pronounced and most of the rays are traveling parallel to each other as seen in the large amplitude of the outer rings. The smaller wavelengths are less intense along the axis of propagation and more intense on the outer rings. Figure 8(d) is the most extreme example which demonstrates how the beam would look if the 800nm standard was used on this axicon. Figure 8(c) shows the other side of the spectrum; the larger wavelength generates a wider beam that retains the Bessel properties. The effect of wavelength on the beam can be adjusted by redesigning the lens. The key property here is that the wavelength can vary by 20 nm and the output still remains usable.
V. CONCLUSION

Free space optics is becoming more common in the field of optical communication. FSO systems provide a solution to optical links where fiber installations are too expensive and radio signals encounter too much interference. The bottleneck in the networks due to electrical devices will be eliminated by moving to all optical devices. As the bandwidth and fidelity of optical networks increases, new optical devices are supposed to match these requirements. The results prove that a simple system of lenses can replace the complex electrical components of the traditional FSO point to point systems. The power delivered by the system is enough for an average avalanche photo diode to receive a signal. The system accommodates fibers with a NA between 0.31 and 0.51 without any adjustments.

The system presented here replaces the conventional electrical components with optical components. The design is also very modular. This is the main advantage of an all optical system. While the electrical FSO point to point link requires numerous cables and protection against the elements, this system requires one cable and would not fail due to adverse weather conditions. Cost is another advantage of this design. Due to the casing and electronics in a traditional FSO system, one side of a traditional FSO system can cost at least $6,000 depending on the range and features needed [7]. The raw material cost of the all optical system is around $20 for each element as estimated by Code V cost estimate tool. This brings the estimated total cost of the whole optical system to less than $100. Furthermore, two simple lenses require much less maintenance and care than two electronic devices.

Future research will be adding on to the basic system to provide all the functionality as the electrical point to point links provide while retaining the advantages of the all optical devices. A tracking method to prevent pointing loss needs to be developed, possibly by using higher order Bessel beams. The compatibility...
of common coding methods and the Bessel Beam needs to be explored as well as a way of positioning the receiver and transmitter when the beams are beyond line of sight. Lastly, different materials must be explored. Reflective lenses would not experience the reflective loss like the refractive materials. Metamaterials working at the terahertz range could provide many advantages as well.

VI. REFERENCES


