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A Novel Method of Wireless Data Transfer Through a Variable Focus Lens-Induced Irradiance Modulation of a Gaussian Beam

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ABSTRACT Mindful of several recent developments in the area of wireless optical data transfer over long and short distances, we present a novel technique to transmit data using an optical carrier. With this technique, the irradiance distribution of a Gaussian optical beam is controlled by passing it through an electronically controlled tunable lens (ECTL). The focal length of the ECTL is controlled by varying the root mean squared voltage of its input electrical drive signal, which alters the irradiance distribution of the Gaussian beam at any fixed plane located after the ECTL. These changes in the irradiance distribution can be interpreted as irradiance modulation with an applied input electrical signal. Variations in the input voltage signal to the ECTL result in variations in the photo-current produced inside a photo-detector of a finite active area. This paper aims to use this unique and simple method for free-space data transfer, and understand the limitations imposed by the currently available commercial ECTL technologies. With rapidly improving ECTL switching speeds and their already widespread use in mobile devices, this method promises an excellent alternative to existing point-to-point wireless data transfer schemes with minimum alterations to the existing hardware architecture of portable mobile devices.

INDEX TERMS Optical modulation, adaptive optics, optical design, wireless data transfer.

I. INTRODUCTION

Electrically controlled tunable lenses were initially developed for bulk motion-free multi-focus cameras in cellphones. ECTLs require low-power electrical signals to drive them and their assemblies are mostly simple, compact and robust. These features encourage the use of ECTLs in numerous applications other than their originally intended deployment in compact multi-focus cameras. ECTLs have been used in a number of applications in optical imaging [1]–[3], microscopy [4]–[6], optical attenuation [7]–[9], sensing [10], [11], to name a few. In this paper, we present a novel concept of beam irradiance profile modulation using an ECTL. According to the proposed method, if the focal length of an ECTL is controlled as a function of time, it can potentially enable us to use variable lensing as a means for wireless data transfer when a photo-detector with a finite aperture is used as a detector.

In prior art, various free-space optical modulation schemes have been proposed. Intensity and frequency modulation of an optical carrier have been achieved using the electro-optic effect [12], [13]. Similarly the acousto-optic effect has been used to achieve intensity modulation through the dependence of diffraction efficiency on the power of an applied modulated acoustic signal [14]. The acousto-optic effect also achieves frequency modulation of the optical carrier as the frequency of an acoustic signal imparts a Doppler Shift on an incoming optical beam [15]. Intensity modulation can also be achieved through the Franz-Keldysh Effect-based electro-absorption process [16]. Multi-wavelength chromatic aberration-based optical modulation has also been proposed in the past [17].

All of these aforementioned techniques of optical modulation have experienced varied degrees of commercial success in industrial and scientific applications. The use of an ECTL to achieve beam irradiance modulation for free-space optical communication is novel and presented here for the first time. The use of an ECTL for wireless data transfer through beam steering has been proposed in prior art [18] but the efficiency of the beam steering technique relies heavily on the free-space distance and for every new transmission distance or the choice of a PD, the height of beam incidence on the ECTL has to be altered to achieve exactly the required beam steering at the PD plane over the entire ECTL focal length tuning range. In an irradiance modulation-based technique, which we propose in this paper, data transfer does not rely on an angular deviation of the optical beam thereby eliminating the need to modify the transmitter design for each unique data transmission link.

In the irradiance modulation technique, a changing input voltage drive signal to the ECTL produces a varying focal length which results in a change in the irradiance profile of the propagating Gaussian Beam at the PD plane. We demonstrate that such an irradiance profile modulation of a beam can be effectively used for data transfer with the use of a PD with a finite aperture. We also demonstrate a mathematical understanding of irradiance modulation through the use of an ECTL.

For an experimental demonstration, a digital data signal is passed on to the input of the ECTL controller which is specifically designed to convert the data signal to the ECTL control signal. This ECTL control signal enables a dynamic focal length control of the ECTL with a dynamically changing voltage of the data signal. This way the focal length was made to follow the voltage which is applied to the ECTL. This dynamic change in the ECTL focal length with a change in voltage levels can be interpreted as the modulation of the ECTL focal length by the input voltage drive signal. Consequently, this focal length modulation is responsible for an irradiance modulation of a Gaussian Beam that passes through the ECTL. A simple Photo-Detector PD then retrieves the input voltage signal at the end of the communication channel, thus completing the data transfer process. The results of the experiment to demonstrate the validity of the proposed scheme are also presented in the paper and discussed in detail.

As ECTLs were primarily designed for motion-free multi-focus cameras, most modern portable devices such as cell-phones and tablets deploy them to realize compact and motion-free inbuilt variable focus camera modules. Due to this prevalent use of ECTLs in various portable devices, the proposed method of data transfer is highly promising as it extends the use of these ECTLs for a point-to-point wireless data transfer between any such pair of mobile devices with minimal changes to the existing architecture of these devices. Albeit slow with the currently available commercial technology, our motivation of proposing this novel method of data transfer is to provide an additional data transfer alternative in mobile devices once the speed of the multi-focus technology improves to support faster data rates.

It is understood that this method of data transfer is not expected to be deployed for current high-speed data transmission networks due to the limited response times of commercially available tunable lenses. The motivation for this paper is exploratory and we emphasize on the development of the basic technical framework for irradiance modulation-based free-space data communication. It is expected that the rapidly evolving switching speeds of current ECTL designs would extend the viability of using this irradiance modulation scheme for future commercial high-speed data transfer applications. Switching speeds of ECTLs in the order of a millisecond have already been demonstrated [19] and improving rapidly. We present the fundamental theory of irradiance modulation through an ECTL as well as a proof-of-concept experiment.

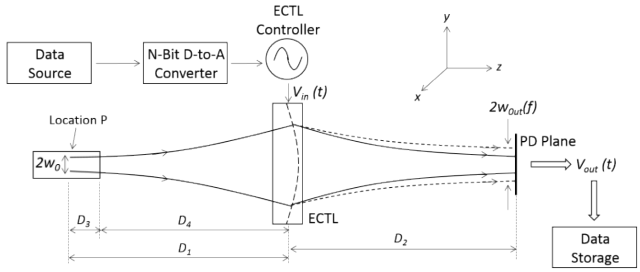

FIGURE 1. Optical setup for wireless data transfer through irradiance modulation of a Gaussian beam.

II. METHOD OF IRRADIANCE MODULATION USING A TUNABLE FOCUS LENS

In this section, we present the proposed mechanism of data transfer system using an ECTL. The method achieves a variation in the irradiance of a Gaussian Beam that passes through an ECTL. This irradiance modulation is achieved through the dynamic control of the ECTL focal length f by varying the RMS amplitude V_{in} of the input voltage drive signal to the ECTL. A time-varying ECTL focal length, induces a corresponding temporal variation in the $1/e^2$ beam radius w_{out} at the plane of a receiving photo-detector. A time-varying spot size w_{out} results in a time-varying irradiance at the detector plane. As is shown in Fig.1, the Gaussian Beam is normally incident on a photo-detector with a finite active area. The PD is placed such that the center of its active area coincides with the center of the incident Gaussian Beam.

As depicted in Fig.1, the Gaussian Beam originates from a Laser Source (LS) and passes through the center of the ECTL. If the ECTL is located at a distance D_1 from the effective location 'P' of the minimum beam radius w_0 behind the exit aperture of the laser source, we know that:

$$D_1 = D_3 + D_4 \tag{1}$$

Here D_3 is the distance of location P from the exit aperture and D_4 is the distance from the aperture to the ECTL. The electric field intensity $E(r, z)$ of a Gaussian Beam is expressed in terms of the complex q-parameter $q(z)$ [20] as:

$$E(r, z) \propto \exp\left(jkr^2/2q(z)\right) \tag{2}$$

Where the complex q-parameter $q(z)$ of the Gaussian beam can be expressed as:

$$\frac{1}{q(z)} = \frac{1}{R(z)} - j\frac{\lambda}{\pi w^2(z)} \tag{3}$$

In (3), λ is the wavelength of light from the LS, $R(z)$ is the radius of curvature of the beam's wavefront at a location z along the optical axis, $k = 2\pi/\lambda$, and $r = \sqrt{x^2 + y^2}$, where (x, y) are the Cartesian coordinates of the optical field plane. Also $w(z)$ is the 1/e^2 beam waist radius at a location z from the minimum waist point P. Substituting $R = \infty$ in (3) results in a completely imaginary q-parameter q_{in} at location P and it is expressed as:

$$q_{in} = j\pi w_0^2/\lambda \tag{4}$$

At the PD plane, the 1/e^2 radius of the beam is w_{out} and its complex q-parameter is q_{out} which is given by:

$$1/q_{out} = (Cq_{in} + D)/(Aq_{in} + B) \tag{5}$$

A PD is located at a distance D_2 from the ECTL. The ABCD matrix [20] for beam propagation from location P to the PD plane after passing through a voltage-controlled ECTL is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & D_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f\,(V_{in}) & 1 \end{bmatrix} \begin{bmatrix} 1 & D_1 \\ 0 & 1 \end{bmatrix} \tag{6}$$

Using (6), the matrix elements A, B, C and D are determined to be:

$$A = 1 - D_2/f\,(V_{in}) \tag{7}$$
$$B = D_1 + D_2 - D_1D_2/f\,(V_{in}) \tag{8}$$
$$C = -1/f\,(V_{in}) \tag{9}$$
$$D = 1 - D_1/f\,(V_{in}) \tag{10}$$

Next, w_{out} is calculated from the imaginary part of $1/q_{out}$, denoted by $im(1/q_{out})$. The expression for w_{out} is given by:

$$w_{out}^2 = \frac{-\lambda}{\pi \cdot im\,(1/q_{out})} \tag{11}$$

From (11), $w_{out}(f)$ is calculated as a function of the ECTL focal length f as is also shown in [21] as:

$$w_{out}^2\,(f) = w_0^2\,(1 - D_2/f\,(V_{in}))^2 + (\lambda/\pi w_0)^2 \times (D_1 + D_2 - D_1D_2/f\,(V_{in}))^2 \tag{12}$$

The optical power detected by the PD depends on the geometry of the PD active area and the magnitude of the 1/e^2 beam waist w_{out} at the PD plane. The number of photons that participate in the generation of a photo-current consequently changes with variations in the irradiance profile of the incident Gaussian Beam, as also shown in Fig.2. A standard trans-impedance amplified PD can be used as a signal demodulator. The PD will detect any changes or fluctuations in the irradiance profile of the optical beam due to the resulting fluctuations in the photo-current. As also shown in Fig.2, the output voltage signal V_{out} is obtained when the photocurrent is measured across a load resistance R_{Load}.

At the receiver, V_{out} is mathematically dependent on the ECTL input voltage drive signal V_{in} and the relationship between V_{in} and V_{out} is the transfer function of the proposed transmitter/receiver system. A successful detection of V_{out} concludes the data transmission process. It is imperative to determine the modulation transfer function of the proposed modulation scheme and understand design limitations. Fig.3 summarizes the data transfer process with our method.

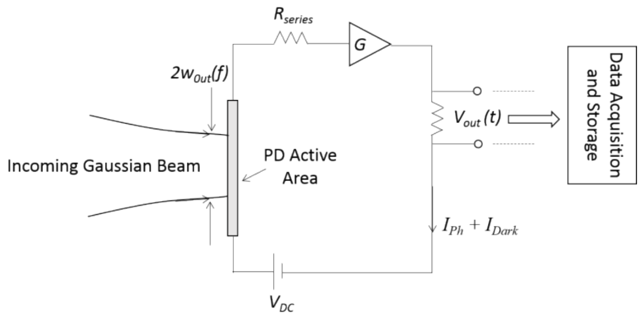

FIGURE 2. **Detection of irradiance modulation with a simple DC-biased PD.**

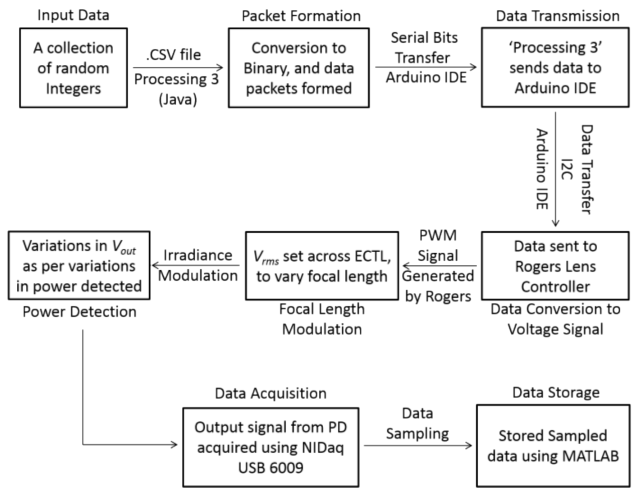

FIGURE 3. **Block diagram of the data transmission through ETCL focal length control.**

To derive an expression for the voltage transfer function for irradiance modulation, we first determine the optical power P_{opt} received by the PD as a function of the ECTL focal length f and the input voltage V_{in}. The relationship between Pout and V_{out} depends on the quantum efficiency of the PD and it is used to calculate the desired voltage transfer function $V_{out}(V_{in})$. We present voltage transfer functions for the two most common geometries of the PD active area; circular and rectangular as shown in Fig.4.

A. VOLTAGE TRANSFER FUNCTION V_{out} (V_{in}) FOR A PD WITH A CIRCULAR ACTIVE AREA

The irradiance profile of a Gaussian beam [22] at any position along the z-axis is given by:

$$I\,(x, y, z) = I_0 \left(\frac{w_0}{w\,(z)}\right)^2 \exp\left(-\frac{2\,(x^2 + y^2)}{w^2\,(z)}\right) \tag{13}$$

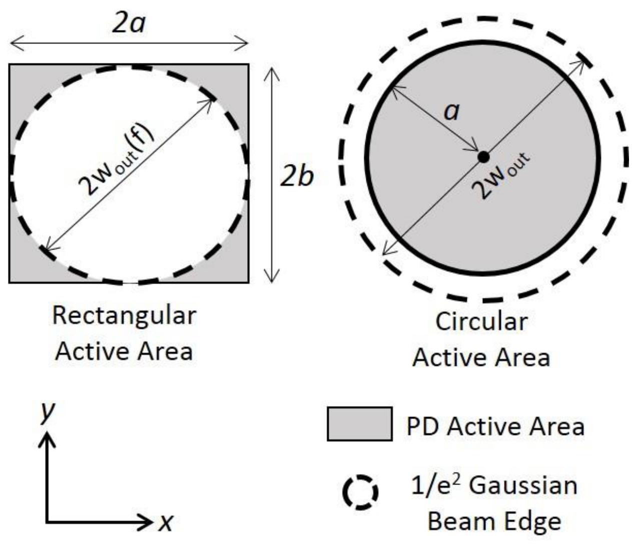

FIGURE 4. Gaussian beam incident on PDs with circular and rectangular active area geometries.

In polar cross-sectional coordinates it is expressed as:

$$I(r,z) = I_0 \left(\frac{w_0}{w(z)}\right)^2 \exp\left(-\frac{2r^2}{w^2(z)}\right) \tag{14}$$

At the receiver (i.e. PD) location $z = z'$, the beam waist radius $w(z') = w_{out}$. Thus the irradiance profile from (14) at the PD plane is given by:

$$I(r,z') = I_0 \left(\frac{w_0}{w_{out}}\right)^2 \exp\left(-\frac{2r^2}{w_{out}^2}\right) \tag{15}$$

The total optical power P_{Total} of the Gaussian Beam can be determined by integrating the two-dimensional Gaussian irradiance function at any infinite plane that is transverse to the z-axis.

$$P_{Total} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y,z)\,dxdy = \int_0^{2\pi}\int_0^{\infty} I(r,z)\,rdrd\theta. \tag{16}$$

Using the standard Gaussian Integral identity at $z = z'$ to obtain P_{Total}.

$$P_{Total} = I_0\left(\frac{w_0}{w_{out}}\right)^2\left(\frac{\pi w_{out}^2}{2}\right) = \frac{\pi w_0^2 I_0}{2} \tag{17}$$

Next, we compute the optical power P_{opt} collected by a circular detector of radius 'a' which is given by:

$$\begin{aligned} P_{opt} &= \int_0^{2\pi}\int_0^{a} I(r,z)\,rdrd\theta \\ &= 2\pi I_0\left(\frac{w_0}{w_{out}}\right)^2 \int_0^a \exp\left(-\frac{2r^2}{w_{out}^2}\right) rdr \end{aligned} \tag{18}$$

Where

$$\int_0^a \exp\left(-\frac{2r^2}{w_{out}^2}\right) rdr = \frac{w_{out}^2}{4}\left(1-\exp\left(\frac{-2a^2}{w_{out}^2}\right)\right). \tag{19}$$

And therefore,

$$\begin{aligned} P_{opt} &= \frac{\pi I_0 w_0^2}{2}\left(1-\exp\left(\frac{-2a^2}{w_{out}^2}\right)\right) \\ &= P_{Total}\left(1-\exp\left(\frac{-2a^2}{w_{out}^2}\right)\right) \end{aligned} \tag{20}$$

Also we know that the beam radius w_{out} at the PD plane depends on the ECTL focal length f as demonstrated in (12). By substituting (12) into (20), the optical power P_{opt}, that produces a photo-current, can be expressed in terms of f in (21), as shown at the bottom of this page.

The value of f is a function of V_{in} and the type of functional dependency, in turn, depends on a particular ECTL model. The resulting PD photo-current I_{ph}, when measured across a load resistance R_{Load}, delivers an output voltage V_{out}. For Trans-impedance amplified photo-detectors the output voltage is described in terms of incident optical power P_{opt} and consequently the input voltage V_{in} in (22), as shown at the bottom of this page.

Here G is the PD trans-impedance gain, $\Re$ is its responsivity and R_{Series} is the internal resistance of the photo-detector. (22) is the desired relationship between V_{in} and V_{out} i.e. the voltage transfer function of the proposed data transfer system and, due to the uniqueness of $f(V_{in})$ for each ECTL model, it depends on the choice of the ECTL model that is used.

B. VOLTAGE TRANSFER FUNCTION V_{out} (V_{in}) FOR A PD WITH A RECTANGULAR ACTIVE AREA

For a PD with a rectangular active area with dimensions of 2a X 2b, the incident optical power P_{opt} which results

$$P_{opt}(f) = P_{Total}\left\{1-\exp\left(-\frac{2a^2}{w_0^2\left(1-D_2/f(V_{in})\right)^2 + (\lambda/\pi w_0)^2\left(D_1+D_2-D_1D_2/f(V_{in})\right)^2}\right)\right\} \tag{21}$$

$$\begin{aligned} V_{out} &= G \times \Re \times \frac{R_{Load}}{R_{Load}+R_{Series}} \times P_{opt} \\ \Rightarrow V_{out} &= G \times \Re \times \frac{R_{Load}}{R_{Load}+R_{Series}} \times P_{Total} \\ &\quad \times \left\{1-\exp\left(-\frac{2a^2}{w_0^2\left(1-D_1/f(V_{in})\right)^2 + (\lambda/\pi w_0)^2\left(D_1+D_2-D_1D_2/f(V_{in})\right)^2}\right)\right\} \end{aligned} \tag{22}$$

in the generation of a photo-current is also calculated by solving a Gaussian integral with rectangular boundary conditions. At $z = z'$, $w(z') = w_{out}$ and P_{opt} is expressed as:

$$P_{opt} = I_0 \left(\frac{w_0}{w(z)}\right)^2 \int_{-a}^{a}\int_{-b}^{b} I(x, y, z)\, dxdy$$

$$\Rightarrow P_{opt} = I_0 \left(\frac{w_0}{w_{out}}\right)^2 \int_{-a}^{a} \exp\left(-\frac{2x^2}{w_{out}^2}\right) dx \int_{-b}^{b} \times \exp\left(-\frac{2y^2}{w_{out}^2}\right) dy \tag{23}$$

Solving (23), we can express P_{opt} in terms of w_{out} as:

$$P_{opt} = \frac{I_0 \pi w_0^2}{2}\left[erf\left(\sqrt{2}\frac{a}{w_{out}}\right)\right]\left[erf\left(\sqrt{2}\frac{b}{w_{out}}\right)\right] \tag{24}$$

Through (12), w_{out} is a function of f and consequently the applied input voltage V_{in} i.e. $w_{out}(V_{in})$. Therefore the relationship between V_{out} and V_{in}, for a rectangular PD clear aperture is given by:

$$V_{out} = G \times \Re \times P_{Total}\left(\frac{R_{Load}}{R_{Load} + R_{Series}}\right) \times \left[erf\left(\sqrt{2}\frac{a}{w_{out}(V_{in})}\right)\right]\left[erf\left(\sqrt{2}\frac{b}{w_{out}(V_{in})}\right)\right] \tag{25}$$

Equations (22) and (25) present the relationships between the input and output voltage signals with either of the two most common PD active area geometries. It is also noticeable that a photo-detector with higher responsivity and trans-impedance amplifier gain would deliver a higher modulation depth as a result of a higher contrast between the highest and lowest possible values of V_{out} for a given range of input voltages V_{in}.

When an N-Bit voltage controller is used to drive an ECTL, it results in 2^N possible levels of the input voltage V_{in}. If the ECTL switching time is ζ seconds, then the maximum achievable bit rate R_B is given by $R_B = N/\zeta$ Bits/sec.

III. DEMONSTRATION OF DATA TRANSFER THROUGH IRRADIANCE PROFILE MODULATION

A. BASIC EXPERIMENTAL SETUP

An experiment was performed to implement the setup in Fig.1 and demonstrate successful data transmission using the proposed method. In our experimental setup, we used a 632.8nm Helium Neon (He-Ne) laser source. The minimum spot size $w_0 = 394.8\mu$m and its location P is estimated to be 40.9cm behind the laser aperture i.e. $D_3 = 40.9$cm. The distances D_4 and D_2 were set to 35.25cm and 6.5cm respectively. Hence $D_1 = D_3 + D_4 = 76.15$cm. The ECTL used for the experiment was the Varioptic Arctic 316 lens with a 2.5mm clear aperture diameter [23].

A Thorlabs PDA10A trans-impedance photo-detector [24] was used as a receiver. The Thorlabs PDA10A PD has a responsivity of $\Re = 0.37$ A/W at 632.8nm and a built-in trans-impedance amplifier with a gain of G = 5000 V/A. The test data which was used for transmission was stored in the CSV file in a Personal Computer (PC) in a single row and was read through Processing 3. Every data value corresponds to a voltage level which was passed on to the serial monitor port of the Arduino IDE from a standard serial port on the PC. Arduino IDE then picks up this value from its serial monitor port and passes it on to the lens controller using the standard I2C protocol.

Since Arduino IDE (i.e. the coding environment for the Arduino board) is not capable of reading csv files directly, we used Processing 3 to read the csv file and transmit the signal to the Arduino IDE and control the serial port communication of the PC to the Arduino input port. Arduino IDE communicated with the Rogers MAAN-060614 I2C lens controller which generated corresponding required voltage signals to control the ECTL. This applied voltage is responsible for varying the ECTL focal length which achieves the desired irradiance modulation of a Gaussian Beam passing through the ECTL. As shown in Fig.3, the test data was stored in a csv file. The data was converted into a binary sequence using standard string to number conversion. This binary data was then represented as a sequence of 8-Bit numbers.

Each 8-Bit number in the sequence is then passed on to the ECTL controller which converts each 8-Bit number to a corresponding Pulse Width Modulated (PWM) Signal with a distinct Root Mean Squared (RMS) voltage value V_{rms} which controls the ECTL focal length. Therefore, to control the ECTL focal length, an Arduino-based controller was designed to accept 8-Bit data packets and generate corresponding standard PWM control signals to drive the Arctic 316 ECTL that we used in our experimental demonstration. Here we find it quite relevant to discuss the ECTL controller which we specifically designed for our proposed system.

B. DESIGN OF THE ECTL CONTROLLER WITH THE Arduino Uno R3 AND THE Rogers MAAN-100622 I2C BOARDS

An ECTL controller was designed specifically to enable us to control the ECTL focal length in real-time. In order to drive the ECTL, the controller was designed to generate PWM signals with a unique V_{rms} value for each input value. The PWM voltage signal that the controller generates must also have an RMS value within a certain range of magnitudes for a complete ECTL focal length control. The required range of the RMS voltage of the PWM control signal is $10\text{V} < V_{rms} < 60\text{V}$ for a complete Varioptic Arctic 316 ECTL.

In our experimental setup, data stored in a csv file was transmitted via the serial port of a personal computer. For the proposed system to work, this data must produce an ECTL focal length modulation, through the use of the Rogers MAAN-100622 I2C controller. The Rogers MAAN-100622 I2C is the standard ECTL controller IC which generates PWM signals with specific V_{rms} values that set the ECTL focal length. The Rogers MAAN-100622 driver board only accepts command signals through its I2C protocol-based I2C input port.

The incompatibility between the serial port data communication protocol, which is used to transfer the original data from the PC, and the I2C protocol, which is the protocol of the Rogers MAAN MAAN-100622 I2C controller, is resolved through the use of an Arduino Uno R3 controller board. The Arduino board was interfaced to the serial port of the PC through its SDA and SCL lines and it relays the serial port data from the PC to the Rogers MAAN-100622 I2C lens driver board through its standard I2C output port. The Rogers controller then processes 8-Bit data segments, relayed by the Arduino Uno R3 board to generate corresponding PWM signals. A successive stream of 8-Bit data segments results in a time varying V_{rms} of the PWM drive signal to the ECTL. This results in a dynamically changing ECTL focal length. The design of our ECTL controller is summarized in Fig.5.

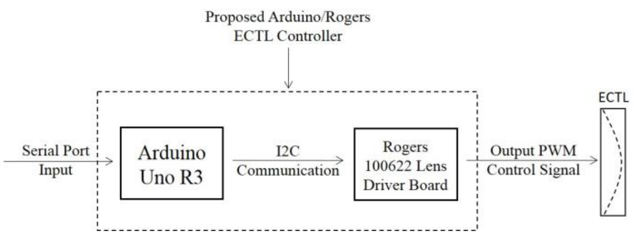

FIGURE 5. Basic design of the Arduino/Rogers ECTL controller modulating the ECTL focal length resulting in the irradiance modulation of the Gaussian beam passing through the ECTL.

C. FOCAL LENGTH AS A FUNCTION OF APPLIED INPUT VOLTAGE TO THE Varioptic Arctic 316 ECTL

As mentioned earlier, the Arctic 316 was used for the experiments keeping in mind that the lens driver board (the Rogers MAAN-100622 I2C Board) is readily available. This was critical to the implementation of a customized ECTL controller design.

The measured focal length at various levels of the input applied RMS voltage V_{in} are available from the Arctic 316 Datasheet [23]. As discussed earlier in (22) and (25), voltage transfer function for any detector geometry eventually depends on how the ECTL focal length varies with the input RMS voltage V_{in}. For the voltage range of operation in our experiment, the relationship between the ECTL focal length f to an applied voltage V_{in} is given in [23] as:

$$\frac{1}{f\,(V_{in})} = 1.714\,(V_{in} - 37.5) \tag{26}$$

As the active area geometry of the Thorlabs PDA10A photo-detector is circular, we substitute (26) in (22) to obtain the voltage transfer function for our experimental setup. This voltage transfer function is plotted in Fig.6.

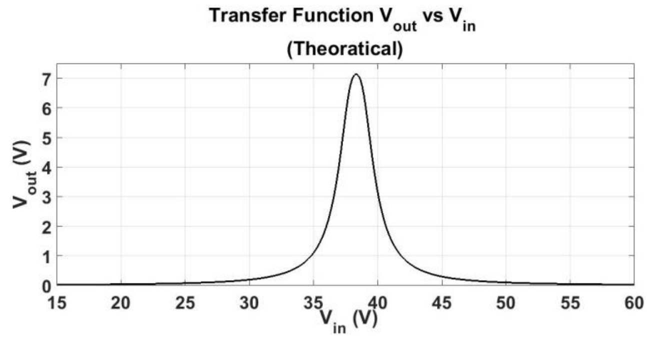

FIGURE 6. Voltage transfer function for the experimental data transmission system using the Arctic 316 ECTL and the Thorlabs PDA10a PD.

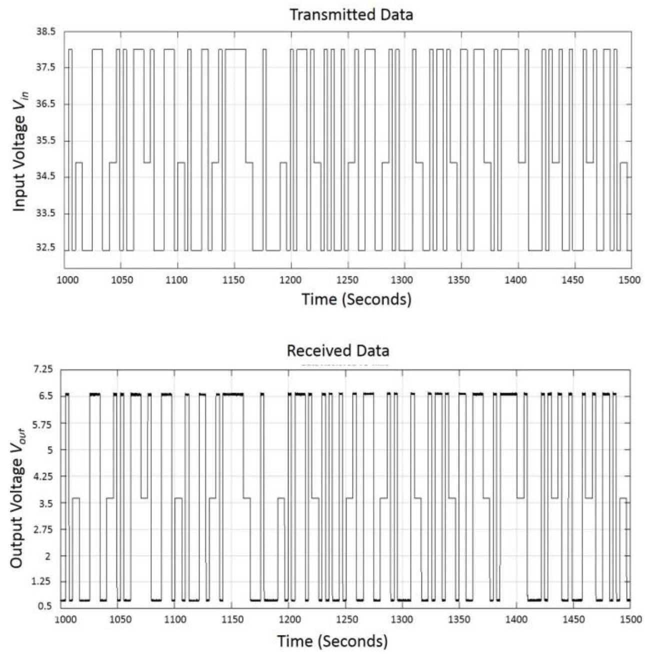

FIGURE 7. Transmitted and received 3-level digital data with the proposed method.

D. DEMONSTRATION OF DATA TRANSFER THROUGH DYNAMIC CONTROL OF THE ECTL FOCAL LENGTH

With the experimental setup described in section 3A and the lens controller described in section 3B, we successfully demonstrate free-space data transfer over short distances. We transmitted a data stream consisting of random 8-Bit numbers. Each 8-Bit number was sent in packets having a length of 14 Bits where the first three bits signify the start of packet and last three bits represent the end of packet.

The irradiance modulated Gaussian Beam was detected by the Thorlabs PDA10A photo-detector. The voltage output of the PD is the measured photo-current, due to the incident optical power, measured across a load resistance. Since the purpose of this paper is to present a proof of concept, data was transmitted in a three level digital form, with one level reserved for the high bit, the second reserved for the low bit

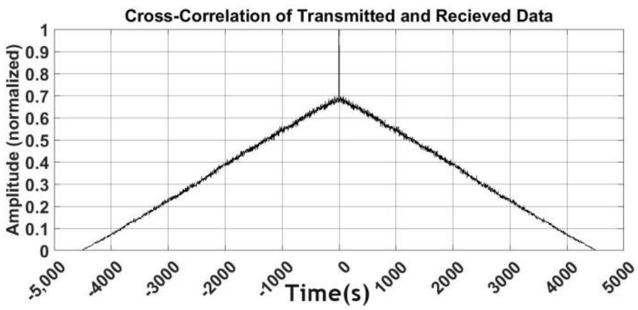

FIGURE 8. Cross correlation of the transmitted and received voltage signals.

and the third level reserved to indicate start and end of a data packet.

For efficient data transfer, it is imperative to operate the ECTL within a voltage range for which a significant change in output voltage is obtained for a unit change in the input voltage. For our experimental setup, from Fig.6, a maximum change in V_{out} for a change in V_{in} (dV_{out}/dV_{in}) is obtained for $V_{in} = 37$V. Therefore we used the voltage levels 38V $> V_{in} >$ 32.5V for the input electrical data signal to control the ECTL focal length.

We transmitted a data stream of 1.365 Mega-Bits with our experimental setup. The data was transmitted in approximately 4550 seconds. A 500 seconds (150 KBits) transmitted and received data segment from the entire data stream is plotted in Fig.7. The V_{out} from the PD were sampled with a National Instrument's NI-USB 6009 data acquisition (DAQ) device which was connected to a data receiving Personal Computer PC2. A standard Matlab application was developed using the Matlab Data Acquisition Toolbox [25] to digitally sample the voltage levels V_{out} through the DAQ and to store the received digital data in PC2. Fig.8 plots the normalized cross-correlation between the transmitted and the received data waveforms. An excellent correlation was achieved between the transmitted and received data.

IV. CONCLUSION

We present a novel method of data communication using an ECTL. The input drive signal to the ECTL modulates the irradiance profile of a Gaussian Beam passing through it. The PD then produces an output electrical voltage signal which is proportional to the optical power it collects. The received voltage signal follows the input voltage drive signal according to the voltage transfer function of the system. Although with current technology the response times of ECTLs are limited but rapid evolution in this technology promises rapid improvements in switching speeds which would enable high-speed wireless data transfer with the proposed method in the future. This method is promising and attractive due to its simplicity, repeatability and cost-effectiveness with minimal changes to existing hardware in mobile devices that already employ ECTLs. We validate our claims through a carefully designed experiment.

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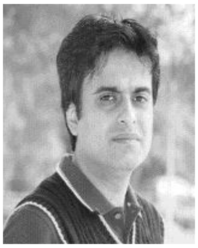

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