Free Space Optical Communication Networks

Peng Deng*[1], Tim Kane[1], Xiuhua Yuan[2], Minghao Wang[1,2], Wentao Xia[1]
[1]Department of Electrical Engineering, The Pennsylvania State University, University Park, USA
[2]School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, China
e-mail: *pxd18@psu.edu

***Abstract*—Effective integration of high speed, power efficient, compact and reliable free space optical communication terminals with small satellite platforms can pave the way to satellite constellations telecommunication networks. This paper will discuss the current architecture limitations that prevent the integration, and the critical technologies to be addressed for the realization of these systems, including compact wide field of view optical antenna, Micro-Electromechanical System (MEMS) gimbal-less fast acquisition and tracking mechanism, spatial diversity and beam shaping techniques for atmospheric channel. This development would explore the landscape of miniaturized high capacity rugged free space optical communication systems for future space networks.**

Keywords-free space optical communication; small satellties, CubeSats; optical antenna; MEMS; beam steering; acquisition, tracking and pointing; spatial diversity; beam shaping.

I. INTRODUCTION

The rapid growth of satellite constellations, enabled by the increasing availability of small-sized and low-cost satellites such as Low Earth Orbit (LEO) Cubesats, can provide global real-time remote sensing and communication network [1]. Data-intensive satellite sensors produce a large amount of information to be transmitted to the ground in a short time, which requires high-capacity communications. Information security is also becoming an urgent issue in satellite constellations, because the amount of critical and valuable data to be communicated is increasing. Tiny satellites such as nanosats and small microsats may lack the power supply or mass for large conventional radio transponders. Small satellite applications are constrained by their ability to provide high bandwidth secured data communications for highly capable payloads [2].

Free Space Optical Communications (FSO) have evolved as a promising alternative for high-capacity data links from space, due to the high gain of a narrow beam, ultralow inter-channel interference and featuring smaller and lighter terminals [3]. Moreover, FSO communications integrated with a quantum receiver, provide a requisite platform for intrinsically hack-proof secure communication, known as Quantum Key Distribution (QKD) [4]. Free Space Optical Communications can enable high speed multi-access space networks [5] to spread across previously inaccessible platforms including satellite-to-satellite crosslinks, up-and-down links between space platforms and aircraft, ships, among mobile and stationary terminals, and other ground platforms. Figure 1 shows Free Space Optical Communication Network [6].

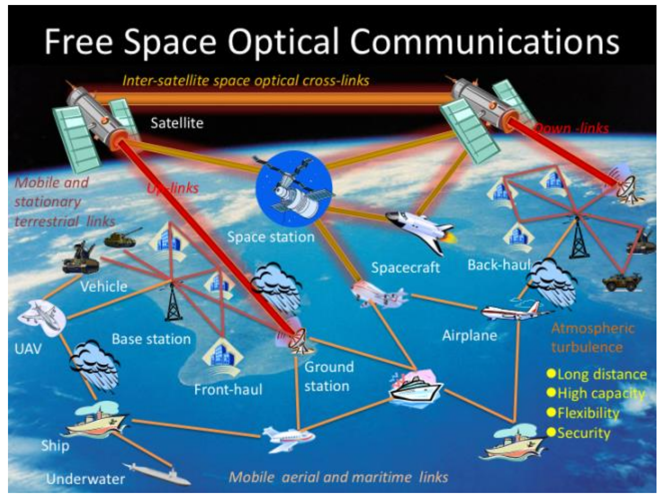

Figure 1. Free Space Optical Communication Network.

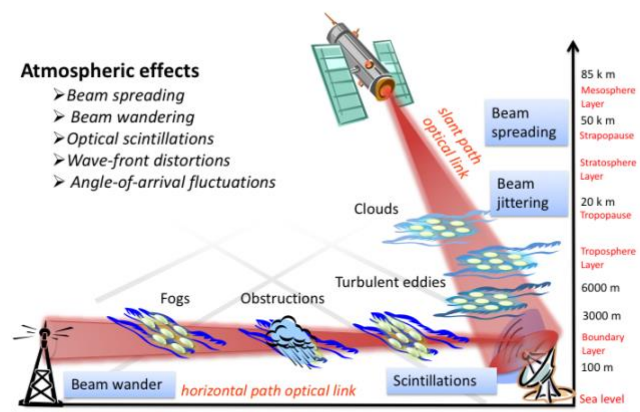

Figure 2. Atmospheric effects on Free Space Optical Communications.

However, traditional FSO system using large size telescope with narrow Field of View (FOV), and power consuming gimbal based Acquisition, Tracking and Pointing (ATP) mechanism [7], cannot meet the requirements of cost and Size, Weight, and Power (SWaP) in nanosatellite applications. Furthermore, atmospheric turbulence induced effects such as scintillations, beam wander and beam jittering can degrade free space optical communication link performance [8][9]. Figure 2 shows atmospheric effects on Free Space Optical Communications [6].

The effective integration of high speed, power efficient, compact and reliable free space optical communication terminals with small satellite platforms can pave the way to satellite constellations telecommunication networks. This paper will discuss the current architecture limitations that prevent the integration of laser communication terminals onboard small space platforms, and explore the critical technologies to be addressed for the realization of these systems. We will discuss compact wide field of view optical antenna [10] in Section II, and MEMS gimbal-less retroreflective acquisition and tracking mechanism [11] in Section III. Section IV presents spatial diversity and beam shaping techniques [12] for atmospheric channel. Fundamental limits of performance and design methodologies for promising future research and development will be given. These technologies would help explore the landscape of miniaturized high capacity rugged free space optical communication systems for the development of future satellites networks.

II. WIDE FIELD OF VIEW OPTICAL ANTENNA

In traditional FSO communication systems, several types of telescopes have been utilized at the front-end of optical antenna, such as Galileo telescopes and Cassegrain telescopes. Schmidt-Cassegrain telescopes are the most popular types of telescopes that eliminate the spherical aberration and compensate for high-order aberration such as coma and astigmatism. It has a slight light loss due to the secondary mirror obstruction compared to refractors. A compact optical antenna using off-axis free form surface triple mirrors [13] was developed to eliminate the obstruction for a high speed laser communication system.

However, the narrow FOV of optical antenna is the inherent characteristic that makes it difficult to maintain the Line-Of-Sight (LOS) links for FSO communications. A compact bidirectional adaptive optical receiver with a wide-angle tracking and adaptive compensation can improve the concentration of laser beam energy and reduce signal fading. Design of a compact adaptive optical receiver utilized fiber-tip positioning systems and piezoelectric bimorph adaptive mirrors for beam steering and low-order wavefront control [14]. In order to observe a large FOV and acquire a wide spatial acquisition range, a correction procedure can be developed [7] from a wide FOV lens imaging model to a pinhole imaging model and used a fisheye lens in a coarse pointing system [15]. In addition, multiple-aperture imaging systems, beam divergence changing mechanisms and an optical phased array receiver can be investigated to improve the optical antenna [16] field-of-view for FSO communications.

Figure 3 shows wide field of view optical antennas for free space optical communications [17]. A wide FOV antenna can be achieved by using a single-element fisheye lens group to collect the wide field beam, and a steering mirror to couple the beam into a multi-mode fiber [10]. The inherent motion environment demands on the accuracy of a tracking mechanical coupling system. Another method to improve the FOV and eliminate the tracking mechanism is to use angle diversity receiver, where an array of narrow-FOV non-imaging receiver elements are oriented along different directions to cover a wide FOV. Diversity schemes such as select-best, equal gain combining [18], and maximal-ratio combining [19] can be employed to improve the received Signal-to-Noise Ratio (SNR) performance. However, implementation of angle diversity using a separate optical receiver for each directional element is excessively bulky and costly. A fly-eye imaging diversity receiver [20], which consists of a single imaging optical concentrator that forms an image of the received light from different directions on a separating element of detector array. Imaging receivers and multi-beam transmitters [21] can reduce the required transmitter power. Moreover, when the multiple beams from multiple receiver elements are spatially separated and independently combined, the effects of intensity fluctuation average out to reduce the probability of signal fades.

An off-axis catadioptric fisheye wide FOV optical antenna for FSO communications [10] is shown in Figure 4. The optical antenna consists of a fisheye lens group and a catadioptric telescope with off-axis aspheric surface mirrors. The optical device elements are numerically analyzed and optimally designed so that the receiver structure can make a positive contribution in enlarging the FOV and reducing optical aberrations. In order to correct the incident beam translation and compensate the beam wandering or beam jittering effects, a double-level tracking mechanism is incorporated into the optical antenna. The purpose of this optical antenna is to provide a 60-degree wide field of view to expand the tracking range, and mitigate optical aberrations to improve the tracking accuracy for FSO systems [10].

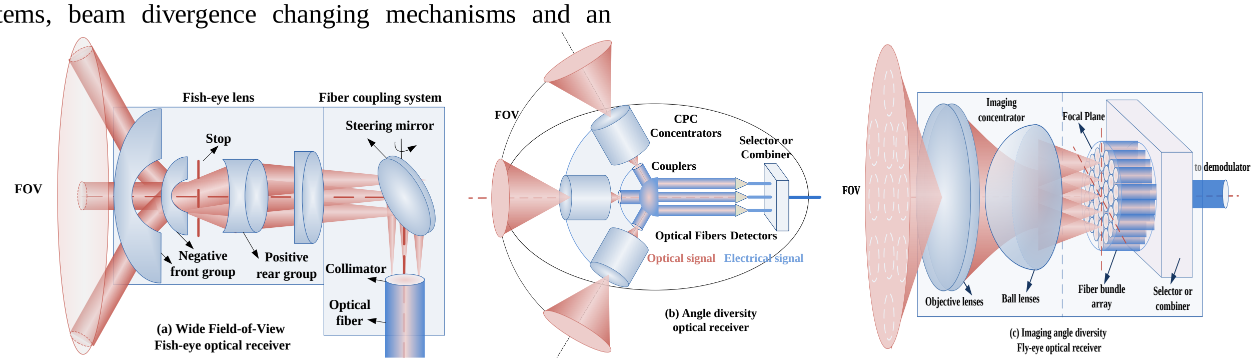

Figure 3. Wide field-of-view optical antennas for free space optical communications [17].

III. MEMS GIMBALESS ACQUISITION AND TRACKING

Free space optical communication system usually employs an ATP mechanism to point the receiver's narrow field of view at the small divergence beam [7]. ATP system, consisting of a coarse pointing system, a fine pointing system, and a point-ahead system, has already been incorporated into a satellite terminal to compensate for the LOS error and dynamic disturbance [5]. However, traditional ATP systems have large size, high power consumption and high cost. The complex coarse pointing system increases weight and volume of optical antenna and reduces tracking efficiency. This approach is impractical for small satellite applications requiring small size and low weight. Thus, a compact and power efficient gimbal-less acquisition and tracking mechanism should be developed for small satellite platforms.

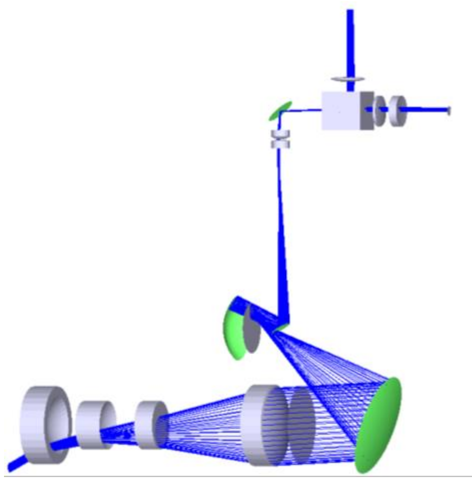

Figure 4. Off-axis Catadioptric Wide field-of-view optical antenna

For acquisition and tracking mechanism, beam steering can be accomplished by changing the refractive index of the medium through which the beam is transmitted or by the use of mirrors, prisms, lenses, or rotating diffraction gratings [22]. Optical beam steering approaches include mechanical mirror-based gimbals, GM mechanisms that rotate mirrors, Risley prisms, phased-array diffraction optics, and Micro-Electromechanical System (MEMS) using micro-mirrors [23]. Conventional mechanical Fast Steering Mirrors (FSMs) using voice coils have large mirrors (25mm) with large moving masses and high power (10W) consumption, which make them more susceptible to shock and vibration. Piezoelectric mirrors offer sufficient steering range (50 mrad) and resolution (5 urad), but piezoelectric actuation exhibits strong nonlinearity and hysteresis which require the use of a complex and large size controller. Galvanometer Mechanisms (GM) have the small size, low cost and large steerable angle (~40 degree), but at the cost of low steering speed (~60 Hz) and high-power consumption (~W). MEMS-based beam steering are much speedier (~kHz), more precise and reliable, and requires a lower power (~mW). Though MEMS beam steering are restricted to small mirrors (1-8mm) or a smaller coverage cone (~10 degree) [23]. We can use a beam expander to adjust beam size or a wide angle field fisheye lens to magnify the optical scan-angles [10]. As a promising beam steering approach within the SWaP constraints, gimbal-less MEMS-based beam acquisition and tracking mechanism can be developed for flexible FSO satellite network.

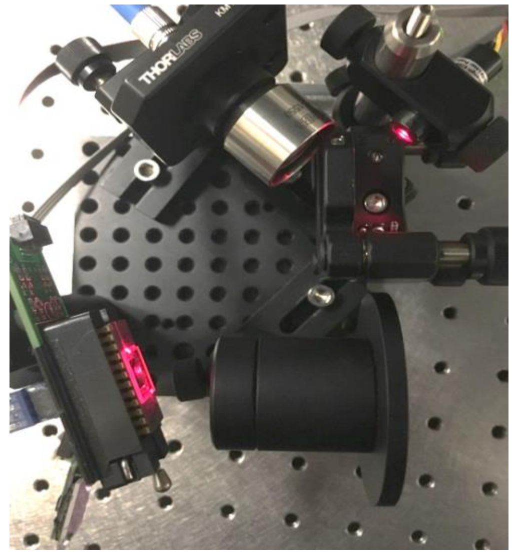

Figure 5. Experiment Setup of 2D MEMS beam steering mechanism to switch Free Space Optical Communication links [11]

For reconfigurable FSO links, we need a beam acquisition and tracking mechanism that can automatically search for the target receiver position quickly, point the beam from transmitter to receiver aperture, and track the center of aperture precisely. Traditional acquisition and tracking using mechanical mirror-based gimbals and electrical feedback signals from the receiver would be lengthy. In addition, a single FSO device assembly, including beam steering and alignment machinery, should have high efficiency in terms of size, cost and power consumption [22]. For this reason, we proposed a separate visible laser beacon based tracking system that integrated a 2D gimbal-less MEMS mirror with retroreflective optics [22]. This system uses a high sensitive photodetector at the transmitter to detect the reflective light from retroreflective tags placed around the receiver apertures. This concept [22] was recently demonstrated for a MEMS beam steerable FSO link working at a data rate above 10 Gb/s [24] with a field-of-view (FOV) of ±4.2◦. Experiment setup of gimbal-less MEMS beam acquisition and tracking mechanism to switch Free Space Optical Communication links for a flexible wireless data center inter-rack network is shown in Figure 5.

With the initial target location, MEMS beam acquisition mechanism auto-search for the target around the initial location within the beam steering angle range. According to various distance and angular directions of retroreflective receiver aperture, we develop intelligent MEMS scanning patterns for beam acquisition and tracking mechanism [11]. The adaptive beam acquisition patterns and tracking algorithm parameters are optimized in term of the acquisition time, searching efficiency and tracking accuracy.

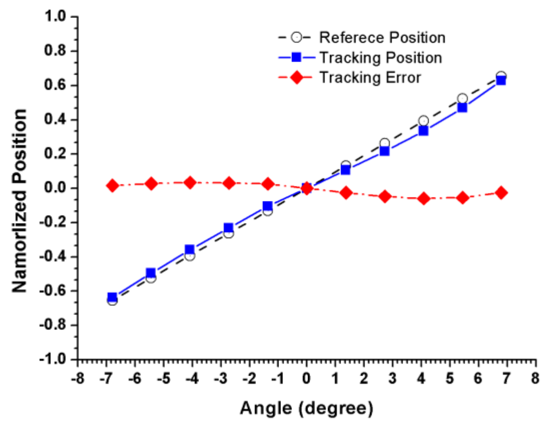

Figure 6. Beam acquisition and tracking position accuracy of MEMS switchable FSO system as function of scan angle [22].

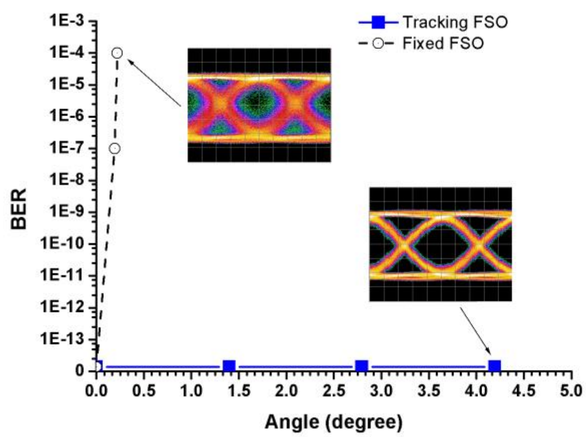

Figure 7. BER performance as function of tracking angle for the fixed FSO link and the MEMS tracking FSO at 10Gbps [22].

An adaptive scan pattern is performed for intelligent acquisition and tracking system, to search and identify the retro-reflective receiver aperture at arbitrary positions within the scanning range of the MEMS mirror [22]. As hitting a retro-reflector, a strong signal peak is detected and associated to the MEMS mirror position. The estimated positions of the retro-reflectors are used as initial values of the reference positions for the line of sight alignment of tracking system [11]. For this experiment, we enhance the distance from MEMS transmitter to retroreflective receiver by using adaptive threshold detection and intelligent acquisition tracking patterns, and improving optical power coupling efficiency. When the retroreflective receiver aperture is moved along a linear transition direction at various distance, beam acquisition and tracking positions and response times are recorded in order to characterize MEMS tracking system with respect to acquisition accuracy and tracking latency. Figure 6 and Figure 7 show tracking position accuracy and BER performance of MEMS beam switchable FSO at 10 Gbps, respectively.

Design and implement of an agile reconfigurable bidirectional 10Gbps FSO system incorporated with intelligent beam acquisition and tracking mechanism is built based on gimbal-less two-axis MEMS micro-mirror and retro-reflective optics [22]. The gimbal-less MEMS reconfigurable FSO links with intelligent adaptive acquisition and tracking are evaluated over various distances and directions to improve the acquisition latency and tracking accuracy [11]. Optical power loss and bit error rate of reconfigurable 10Gbps FSO links with mobility are evaluated over a short distance. The long distance FSO system can be achieved by using high power lasers such a s MOPA and EDFA, high sensitive photodetectors of APD single photon detectors and high gain wide field-of-view optical antennas. Further research work will focus on long distance bidirectional reconfigurable free space optical communication links using advanced MEMS adaptive acquisition and tracking to address environment effects such as LOS blockages, vibrations and intensity fluctuations.

IV. SPATIAL DIVERSITY AND BEAM SHAPING

Intensity fluctuations or scintillation of laser beam propagation through atmospheric turbulence will degrade the BER performance and channel capacity of free space optical communications between satellites and ground platforms. In order to improve communication performance, scintillations can be mitigated by means of spatial diversity using multiple transmitted beams and multiple receivers [25], reducing spatial coherence of the transmitted beam [26] and advance beam shaping techniques.

A. Spatial diversity and Spatial coherence

Spatial diversity using multiple transmitted beams and multiple receivers can also be employed to reduce scintillation and ultimately improve FSO channel capacity. It has been shown that the scintillation of a beam array can be reduced by carefully adjusting the spatial separation of beamlets [25][27]. However, scintillation of a beam array will increase significantly if the spatial separation of beamlets is smaller than the correlated length. In addition, the received energy from the beam arrays is low unless the constituent beamlets are inclined to overlap at the receiver aperture, which is difficult to achieve over long propagation distances. The use of multiple transmitters and receivers has also been suggested for use in Multiple-Input–Multiple-Output (MIMO) configurations [27].

Partially coherent beams with reduced spatial coherence show lower scintillation at the cost of larger divergence angle and lower average received power. Partially coherent beams have a lower scintillation than fully coherent beams. However, a partially coherent beam has a larger beam spreading and forms a large spot in the receiver aperture, which leads to a loss of the transmitted energy being received by the detector. By optimizing the spatial coherence length, the improvement in scintillation reduction can overcome the penalty of power reduction and significant signal-to-noise ratio gains can be obtained in weak atmospheric turbulence [28].

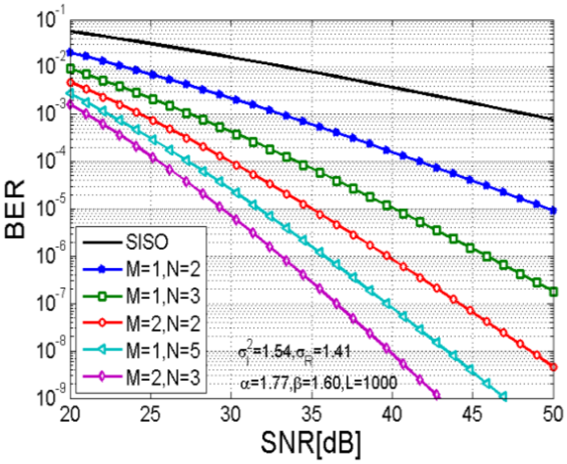

Figure 8. BER performance of MIMO free space optical communications in atmospheric turbulence [17].

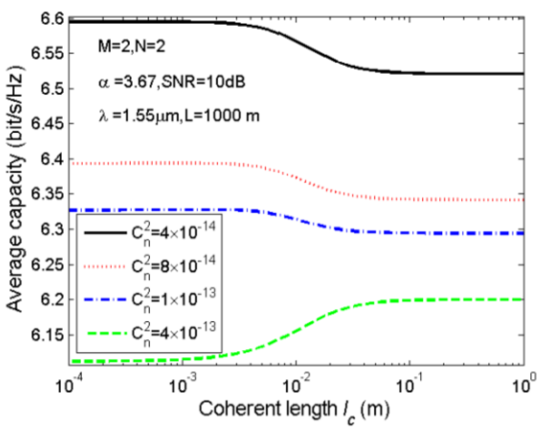

Figure 9. Channel capacity of MIMO free space optical communications using multiple partially coherent beams [12].

However, MIMO FSO links studied so far employ the fully coherent beams whose spatial correlated length is large and the induced scintillation is strong. The mutually independent MIMO branches require a relatively larger separation between the transmitter and receiver apertures than the correlated length. Partially coherent beams with shorter spatial coherence lengths can help reduce the scintillation and correlation length in strong turbulence, and eventually reduce the required separation space between independent apertures [12]. Thus, we proposed to develop MIMO FSO links whose spatially separated beamlets can have lower spatial coherence lengths that lead to reduced scintillation and smaller separation between transmitter and receiver apertures [12]. BER performance of MIMO FSO links in non-Kolmogorov moderate to strong turbulence was evaluated in Figure 8, and the effect of spatial coherence length of partially coherent beams on capacity of MIMO FSO links [12] was analyzed in Figure 9. The approach that incorporates partially coherent beams into the MIMO FSO links could reduce scintillations and correlation length and to improve average channel capacity in weak-media atmospheric turbulence. In strong turbulence, large scale size of turbulent eddy will become shorter than the spatial coherence length, which lead to the increasing large-scale log-irradiance variance and the decreasing average capacity.

B. Beam shaping and Airy beams

Beam shaping is the process of redistributing the irradiance and phase of a beam of optical radiation. The beam shapes is defined by the irradiance distribution and the phase of the shaped beam is a major factor in determining the unique propagation properties of the specific beam profiles, such as Bessel beams, Laguerre beams, Vortex beams and Airy breams. Airy beams exhibit non-diffraction property that can propagate over many Rayleigh lengths without any appreciable change in intensity profiles [29]. Moreover, Airy beams resist diffraction while their main intensity maxima or lobes tend to transversely accelerate during propagation along parabolic trajectories in free space. The self-bending behavior persists over long distances, although the center of gravity of these wave packets remains constant and diffraction eventually takes over. It is also shown that Airy beams have the self-healing properties and can self-reconstruct after propagating through obstacles and retain their intensity profiles under turbulent conditions [30]. Therefore, the non-spreading, self-bending and self-healing properties of Airy beams can make them serve as robust propagation beams resilient against atmospheric turbulence.

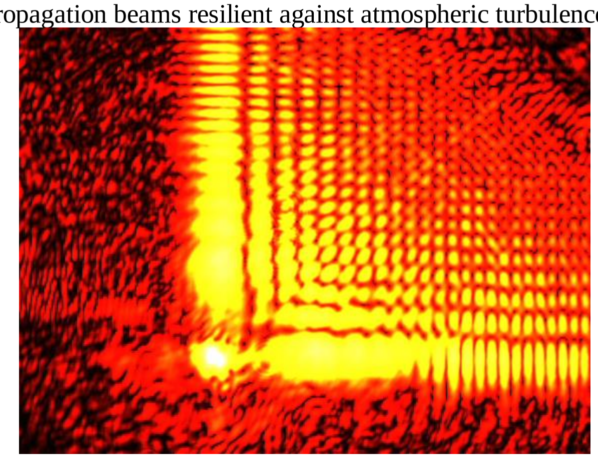

Figure 10. Self-healing of Airy beam propagation through obstructions.

The irradiance and phase distribution of Airy beam are controlled and generated by using a Spatial Light Modulator (SLM) or a hologram phase screen. The SLM is displayed by the Airy beam hologram that consists of the superposition of a 2D phase mask and a diffraction grating. The first order of diffraction is then Fourier transformed using a lens to generate Airy beams. The generated amplitude and phase distribution of Airy beam determine the self-bending and self-healing propagation properties through free space, scattering media and turbulent media as shown in Figure 10. The performance optimization as a function of beam parameters such as coherence length, characteristic length, aperture coefficient and deflection coefficient can be explored to mitigate intensity fluctuation and improve free space optical communication performance.

V. CONCLUSION AND FUTURE WORK

The effective integration of high speed, power efficient, compact and reliable free space optical communication terminals with small satellite platforms can pave the way to satellite constellations telecommunication networks. This paper discussed the current architecture limitations and explore the critical technologies, such as compact wide field of view optical antenna, MEMS gimbal-less retroreflective acquisition and tracking mechanism, spatial diversity and beam shaping techniques for atmospheric channel. Further research will focus on long distance MEMS reconfigurable free space optical communication to address environment effects such as LOS blockages and intensity fluctuations. These technologies would help explore the landscape of miniaturized high capacity rugged free space optical communication systems for future satellites networks.

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