Research on Retro-reflecting Modulation in Space Optical Communication System

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Abstract. Retro-reflecting modulation space optical communication is a new type of free space optical communication technology. Unlike traditional free space optical communication system, it applys asymmetric optical systems to reduce the size, weight and power consumption of the system and can effectively solve the limits of traditional free space optical communication system application, so it can achieve the information transmission. This paper introduces the composition and working principle of retro-reflecting modulation optical communication system, analyzes the link budget of this system, reviews the types of optical system and optical modulator, summarizes this technology future research direction and application prospects.

1. Introduction
Nowadays, with the progress of society and the development of science and technology, the transmission of a large amount of information data has put forward higher and higher requirements on the capacity of communication channels and communication rates, and also proposed higher demandon environmental adaptability for communication technology. Although the communication bandwidth of the optical fiber communication is broadband, it needs to lay the optical fiber network, so it lacks the flexibility. Free Space Optical (FSO) communication is a two-way communication system that transmits information by laser in free-space channel. It has the advantages of large communication bandwidth, large channel capacity, large optical gain and etc. It is one of the technical solutions to achieve high-speed and high-capacity communications, and it widely used in various fields. Traditional FSO links need to have lasers emitting and receiving systems at both ends and sophisticated Acquisition Tracking and Pointing (APT) system that increases system weight, size, power consumption, technical complexity and become the important factor in FSO-constrained applications. Free space optical communication based on Modulating retro-reflector (MRR) can eliminate the transmitting and receiving system and APT system at one end of the communication link [1], greatly reducing the weight, volume and power consumption. In the rapidly developing in UAVs, small satellites, military communications platform has obvious application advantages.
2. Retro-reflecting modulation in the space optical communication system

2.1. System composition and working principle

Free space optical (FSO) communication is a wireless communication method that uses laser as carrier and atmosphere as channel. The traditional space optical communication system generally consists of two terminals: transmitter and receiver, and they are respectively placed at both ends of the communication system. Two terminals are required to perform alignment and tracking with a complicated APT system to achieve point-to-point communication. MRR FSO system is an asymmetric free-space optical communication system, including two asymmetric terminals: the active terminal and the modulating reflection terminal. The schematic diagram of the working modes of the two communication systems is shown in Figure.1. The first conventional mode of operation is commonly used in interstellar free space optical communications links, but the weight of the terminals is very large. For example, satellite terminals in the star-to-earth optical communication system in the ESA SILEX program weigh up to 160 kg. The second generation satellite terminals also weigh 35 kg [2]. The second modulation-reflecting mode of operation is ideally suited for applications such as UAVs and microsatellites such as the NAL for system-wide end-to-end optical communication between ships and ships, ships and unmanned aerial vehicles only 1 kg [3], it far less than the traditional FSO communication system.

![Figure 1](image1.png)

**Figure 1.** The two operational mode of FSO communication system

The second mode with MRR FSO system shown in Figure.2. The active terminal that is the traditional FSO transmitter and receiver terminals, including laser launch system, laser receiving system, signal processing system and control system. The modulating reflection terminal comprises three parts of MRR system, signal processing system and control system. The MRR system includes a spatial light modulator and an optical system. The spatial light modulator is used to implement spatial light modulation. The optical system is used to reflect the light beam back to the receiving system at the active terminal.
The working principle of the MRR FSO system is that the active terminal emits a laser beam (interrogating the beam) to the MRR system. When the modulating reflection terminal detects the interrogating beam, the signal processing system converts the obtained signal into a driving signal of a spatial light modulator, driving the light modulator to load the data of the interrogating beam and implement the modulation. The modulated data beam is reflected by the optical system back to the active laser receiving system, and the receiver hands the acquired data beam to a signal processing system to process the signal [4].

2.2. The link budget of retro-reflecting modulation

The link loss of traditional free space optical communication link is generally in accordance with the law of square inverse of e^{-\alpha R^2} in beam propagation, where \alpha is the loss factor and R is the propagation distance [5]. However, for the FSO MRR communication system link, the transmission link loss is more severe, resulting in e^{-2\alpha R^4} ratio attenuation, because the transmitting beam from the active side experiences a transmission loss and then occurs again after modulated reflection Decay. Therefore, the active terminal of the energy consumption than the traditional FSO communication system. MRR link budget is as follows [6]:

\[ P_r = P_t \frac{A_{\text{ret}} A_{\text{rec}} T_{\text{atm}}^2 \beta y}{\Omega_r \Omega_{\text{ret}} R^4} \]  \hspace{1cm} (1)

Where R is the link distance, P_t is the energy of the interrogating beam, P_r is the energy of the data signal received by the active terminal, A_{\text{ret}} is the aperture of the modulated reflector, A_{\text{rec}} is the aperture of the receiver, T_{\text{atm}} is equal to e^{-\alpha R} is the atmospheric transmission Where \beta is the modulation index of the MRR link, \gamma is the scintillation coefficient, and \Omega_r and \Omega_{\text{ret}} are the solid angles of the interrogating and modulating beams, respectively.

The MRR link experiences two transmit attenuations over two spatial channels, which greatly affects the antenna gain, modulation rate, and modulation bandwidth of the modulated reflectors. In order to overcome such a large transmission loss, the MRR terminal must establish a higher optical antenna gain. The MRR end receives both the transmitted beam from the active end and the reflected data beam to the active end. Therefore, its optical antenna gain must take into account the receive gain and transmit gain, the classic antenna gain formula is as follows:

\[ G_{\text{MRR}} = \left[ \frac{\pi D_{\text{retro}}}{\lambda} \right]^4 \cdot s \]  \hspace{1cm} (2)
Where $D_{\text{retro}}$ is the optical aperture of the modulated reflector, $\lambda$ is the wavelength of the laser, and $S$ is the strehl ratio of the optical system in the modulated reflector \(^7\). It can be seen from formula (2) that the aperture of the modulated reflector determines the optical gain of the MRR terminal.

### 3. Modulating reflection system

The core of the retro-reflecting modulation optical communication system is the modulating retro-reflector (MRR), which includes an optical system and a spatial light modulator. The optical system allows the interrogating beam to be returned along the original optical path. The optical modulator is used to implement spatial light modulation, thereby forming a closed-loop communication optical system with the active terminal.

#### 3.1. The optical system

**3.1.1. Corner cube.** The corner cube is a three-sided right-angle prism that reflects a variety of light or beams that reach the prism surface, reflecting incident light back to the original light path, irrespective of the direction the light enters.

Based on the characteristic that the cube-corner can return the incident beam to the original path, the spatial optical modulator is placed on one surface of the corner cube to modulate the incident beam, and then the modulated data beam is reflected back by the corner cube to the active receiver and processing, so as to achieve the purpose of information transmission. Figure 3 shows the schematic diagram of the reflected light modulation link when using corner cube. The corner cube is simple and convenient to manufacture and low in cost. However, when the corner cube is used as the optical system of the MRR, the size of the optical modulator is required to match the diameter of the corner cube. The larger the size of the optical modulator, the lower the modulation rate, this appeared the contradiction between optical system aperture and modulation rate \(^4\).

**Figure 3.** The retro-reflecting modulation link diagram with corner cube.

**3.1.2. Cat's eye system.** Cat's eye system is composed of a lens and photosensitive surface, the incident beam through the lens to the photosensitive surface, the light beam reflected by the photosensitive surface in accordance with the original light path back. The cat-eye reflected light beam has the original return and collimation characteristics, and the return path characteristics are not affected by the incident light beam, while the cat's eye reflected light intensity is 2~4 orders of magnitude higher than that of normal diffuse reflection \(^8\).

The modulator is placed on the photosensitive surface at the focal plane of the cat's eye system. The incident light beam reaches the light modulator via the cat's eye. After the data is loaded on the light beam, the data beam is reflected to the original end of the optical receiver, to achieve link communications. Because the cat's eye optical system focuses the incident beam to a very small spot at the focal plane position, a small-size modulator can be used to match the large-aperture optical system to achieve a higher modulation rate. Figure 4 shows the schematic diagram of the modulation scheme of the reflected light when the cat's eye system is used.
3.2. The Spatial light modulator

3.2.1. Multiple Quantum Well (MQW) modulator. The MQW modulator was originally proposed by the Navy Research Laboratory (NRL). The MQW modulator shown in Figure 5 consists of an N-type GaAs substrate, a multi-quantum well with a fixed InGaAs/AlGaAs. The quantum well layer is covered by a thin layer of highly doped P-type InGaAs. The working wavelength is determined by multiple quantum well layers, and the common working wavelength is about 1550 nm.

In 2000, NRL installed a 5mm-diameter MQW MRR on a small rotor UAV to realize the principle test of communication speed of 400Kbps ~ 2Mbps and communication distance of 35 ~ 65m. In 2006, the research on long-distance communication using cat's lens was carried out to realize the laser communication experiment with a communication distance of 7km and a communication speed of 45Mbps[9]. NRL and NASA jointly conducted the MODRAS (ModulatingRetro-reflector Array in Space) experiment. The experimental design indexes are: communication speed 12Mbps, satellite orbit height 400km and communication wavelength 1064nm [5]. Figure 6 shows the schematic diagram of the communication between NASA’s mother star and small satellite in the United States.

3.2.2. MEMS (micro-electro-mechanical system) modulator. MEMS modulator is a micro-mechanical deformable mirror or diffraction grating structure, the communication range of 0.1~10km, the use of deformable mirror MEMS remote modulation rate of 100kHz, the use of diffraction grating structure MEMS modulator maximum modulation speed of up to 1Mbps, but this time A mechanical deflection of \( \lambda/4 \)is required and the wavelength and angle of the modulator need to be matched so that the usable field of view is usually only 6 degree or less. MEMS modulators are much slower than MQW modulators, but at a much lower cost and environmentally sensitive than MQW modulators. Figure 7 shows the MEMS modulator proposed by Trevor K Chan and Joseph E Ford [11].
3.2.3. **Acousto-optic modulator.** Acousto-optic modulators consist of acousto-optic media and piezoelectric transducers. When a particular carrier frequency of the driving source drives the transducer, the transducer generates ultrasonic waves of the same frequency and is transmitted to the acousto-optic medium to form a refractive index acoustic change in the medium, and the light beam changes through the interaction of the medium the direction of light is diffracted, as shown in Figure.8.

![Figure 7](image1.png)  ![Figure 8](image2.png)

**Figure 7.** The schematic of MEMS modulator. **Figure 8.** The schematic of Acousto-optic modulator.

In general, the speed of liquid crystal light modulators and MEMS electro-optic modulators is less than 100 kHz, which can not meet the demand of high-speed communications. Based on the bragg diffraction, the acousto-optic modulator is very sensitive to the beam angle and has a viewing angle of only 1°~2°, which is not suitable for the application of free space optical communication between moving platforms. MQW modulator is light weight, low power consumption, high modulation rate, suitable for platform movement to achieve communication, lower operating voltage drive, as well as a larger field of view, is the current reflected light modulation communication system used mainly modulator.

4. **Conclusion**

According to the analysis of the composition and working principle of the retro-reflecting modulation optical communication system and the discussion of the type of modulation retro-reflector, the MQW has a higher modulation rate, and the cat's eye can solve the contradiction between the optical system and the optical modulator. Therefore, the cat's eye with MQW in MRR system will become the main research direction of MRR FSO technology. The experiment of communication link using MRR FSO system is mainly asymmetric point-to-point communication, which is dominated by simple amplitude modulation. Studying the impact of efficient source modulation and channel modulation on the performance of MRR FSO system, and carrying out long-distance full-duplex communication and non-point-to-point communication are important research contents and research directions of future MRR FSO communication system.

The communication link can be widely used in communication link, such as unmanned aircraft, aircraft, reconnaissance vehicle, satellite, underwater and so on with limited load, power consumption and volume road. If the communication link cooperates with the radio frequency communication, it can realize the safe and reliable information transmission. With the development of modulators, the MRR FSO system can achieve Gbps or even higher transmission rate, which will be of great significance for the future development of FSO communication.

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