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Uplink satellite optical communication based on acousto-optic modulator

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Abstract. High-speed data transfer is becoming increasingly necessary for modern satellite communication systems. To address growing bandwidth demands, optical technologies are proposed. Here we investigate an approach to designing an uplink optical communication system based on the acousto-optic modulation scheme. The preliminary findings suggest the applicability of this strategy to provide reliable communications with data rates up to 2.4 Mbps and a bit error rate of 10^{-9}.

Keywords: satellite optical communications, acousto-optic modulator, Manchester encoding

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Восходящая спутниковая оптическая связь на основе акустооптического модулятора

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Аннотация. Высокоскоростная передача данных становится все более необходимой для современных спутниковых систем связи. В связи с этим для удовлетворения растущих потребностей предлагается использовать оптические технологии. Здесь мы исследуем подход к разработке системы оптической связи со спутником на основе схемы акустооптической модуляции. Предварительные результаты показывают применимость этого подхода для обеспечения надежной связи со скоростью передачи данных до 2,4 Мбит/с и частотой битовых ошибок 10^{-9}.

Ключевые слова: спутниковая оптическая связь, акустооптический модулятор, манчестерское кодирование

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Introduction

Modern satellite communication systems are experiencing growing demand for high-speed data transmission, driven by advancements in Earth remote sensing [1–3], inter-satellite communications [4–6], and satellite-based quantum key distribution [7–9]. The integration of laser communication into these fields—as opposed to traditional radio frequency technology – has emerged as a promising solution to meet this demand and offering higher bandwidth, lower latency, and greater resistance to electromagnetic interference. To address this challenge, our team deployed the Impulse-1 satellite (a 6U CubeSat) in 2023, with the goal of demonstrating bidirectional free-space optical communication [10].

To date, research has predominantly focused on downlink communication channels rather than uplinks, as the volume of downlink data significantly exceeds that of uplink transmissions. Moreover, uplink signals experience greater atmospheric attenuation due to turbulence and scattering, which demands a high-power laser source and external modulation. In this work, we present an optimized ground-to-satellite laser communication system based on a high-power laser module, a free-space acousto-optic modulator (AOM), and Manchester encoding.

Methods and Results

External modulation of the laser beam is achieved through Bragg diffraction in an acousto-optic crystal. A piezoelectric transducer converts an applied radio frequency (RF) signal into an ultrasonic wave that propagates through the crystal. The resulting ultrasonic wave induces periodic variations in the crystal's refractive index, creating a volumetric phase grating within the material. The diffraction order depends on the incident light angle relative to the modulator. The maximum diffraction efficiency is achieved when the laser beam enters the crystal at the Bragg angle. This angle can be calculated using the Wulff–Bragg condition:

$$\theta_B = \arcsin\left(\frac{\lambda}{2n\Lambda_a}\right) = \arcsin\left(\frac{\lambda f_{RF}}{2nV_s}\right), \quad (1)$$

where λ is the wavelength of incident light, Λ_a is the acoustic wavelength, n is the refractive index of the acousto-optic crystal, f_{RF} is the frequency of the ultrasonic wave, and V_s is the speed of sound in the crystal.

The diffraction efficiency and amplitude modulation of light can be expressed as

$$\eta = \sin^2\left(\frac{\pi}{\lambda\sqrt{2}}\sqrt{\frac{L}{W}M_2 P_{RF}}\right), \quad (2)$$

where L and W are the length and width of the piezoelectric transducer, M_2 is the acousto-optic quality factor, and P_{RF} is the RF signal power.

The intensity of the diffracted light can be varied by adjusting the P_{RF}. In our case, the maximum efficiency value was 85%. The main system parameters are listed in Table 1.

Table 1

Main system parameters

Optical parameters		Acoustic parameters					
λ	808 nm	f_{RF}	68 MHz	n	1.46 (SiO_2)	L	30 mm
P_{TX}	35 W	P_{RF}	20 W	V_s	5960 m/s	W	5 mm
P_{RX}	5 μW	θ_B	3.2 mrad	$T_{rise/fall}$	40 ns/mm	M_2	1.56e–15 m^2/W

Notations: P_{TX} and P_{RX} are the optical powers of transmitter and receiver, respectively.

The AOM can be controlled using an RF driver, which is equipped with analog and digital inputs. The analog input adjusts the amplitude of the output RF signal. The digital input controls the signal waveform. By default, the driver's output RF signal is a sinusoidal waveform with a frequency of 68 MHz. Fig. 1 shows the experimental setup for testing optical communication technology.

The proposed communication system employs a multimode fiber laser module with a power output of 35 W. For experimental validation, we used a commercial single-mode 808 nm laser diode as the light source, integrated into a custom-designed driver and coupled via multimode fiber to a collimator. The emitted light was focused by a lens into the center of the AOM crystal and then recollimated using the same lens to minimize divergence. The incidence angle was

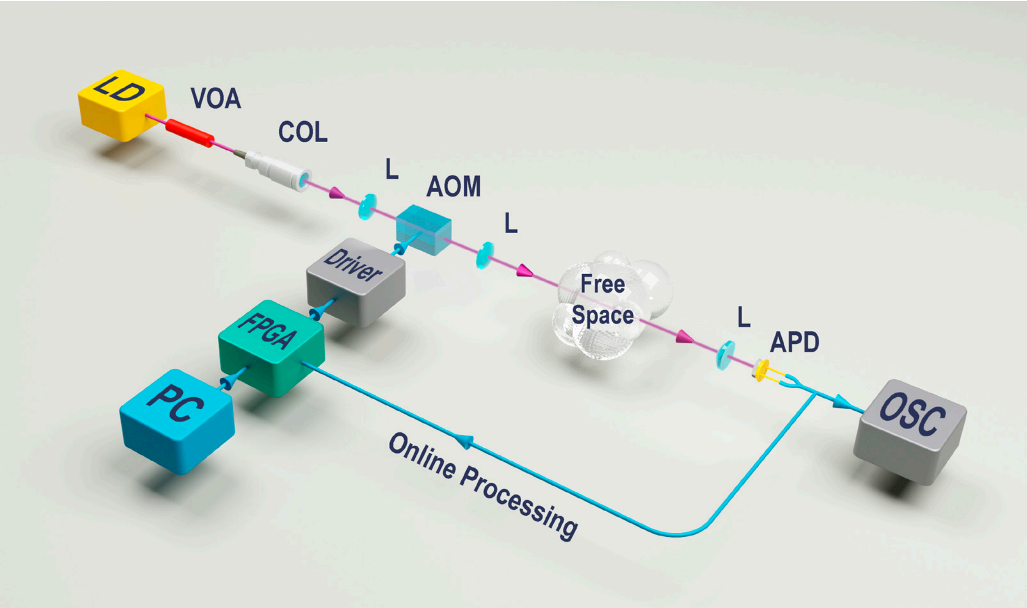

Fig. 1. Experimental setup for demonstrating of the communication system:
LD is the laser diode, VOA is the variable optical attenuator, COL is the collimator, L is the lens, AOM is the acousto-optic modulator, APD is the avalanche photodiode, OSC is the digital oscilloscope, FPGA is the field-programmable gate array, PC is the personal computer

precisely adjusted to maximize diffraction efficiency. The field programmable gate array (FPGA) generates the data signal and transmits it to the AOM driver. At the physical layer, we used Manchester encoding. The modulated laser beam was then focused onto an avalanche photodiode for optical-to-electrical signal conversion. The electrical signal was recorded using a digital oscilloscope and further processed by the FPGA.

We evaluated the modulation depth (MD), quality factor (Q), and bit error rate (BER) across different data rates at an optical power of 5 μW. At data rates up to 2 Mbps, the MD equaled 100%, while at 4 Mbps, it decreased to 50% (see Fig. 2, *a*). For error rate assessment, we adhered to the stringent industry standard of BER $\leq 10^{-9}$ [11, 12], which requires an $Q \geq 6$ [13]. The system meets these specifications at data rates up to 2.4 Mbps (see Fig. 2, *b*).

a) *b*)

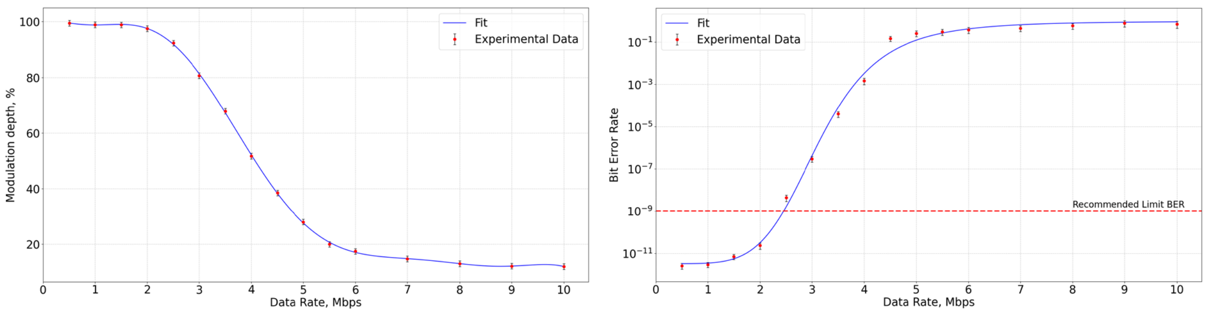

Fig. 2. Characteristics of the communication system measured in laboratory: modulation depth (*a*) and bit error probability (*b*)

System performance parameters are calculated by following equations:

$$\text{MD} = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}, \tag{3}$$

where $P_{\max}$ and $P_{\min}$ are the optical powers that define the modulation depth;

$$Q = \frac{P_s^1 - P_s^0}{P_n^1 - P_n^0}, \tag{4}$$

where P_s^1, P_s^0, P_n^1 and P_n^0 are the optical power levels associated with the signal and noise while encoding bits “1” and “0”;

$$\text{BER} = \frac{1}{Q\sqrt{2\pi}} \exp\left(-\frac{Q^2}{2}\right). \tag{5}$$

Conclusion

The maximum data rate at a specified BER was determined experimentally. We have demonstrated that laser communication with a satellite as part of the Impulse-1 mission is feasible using a technical solution such as acousto-optic modulation based on Manchester encoding at 2.4 Mbps with BER of 10^{-9}.

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