Nuclear Inst. and Methods in Physics Research, A 887 (2018) 18–26

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Temporal characteristic analysis of laser-modulated pulsed X-ray source for space X-ray communication

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ARTICLE INFO

Keywords:
Space communication
Pulsed X-ray source
X-ray communication
NEA GaAs photocathode
Micro-channel plate
Temporal characteristic

ABSTRACT

X-ray communication (XCOM) is a new communication type and is expected to realize high-speed data transmission in some special communication scenarios, such as deep space communication and blackout communication. This study proposes a high-speed modulated X-ray source scheme based on the laser-to-X-ray conversion. The temporal characteristics of the essential components of the proposed laser-modulated pulsed X-ray source (LMPXS) were analyzed to evaluate its pulse emission performance. Results show that the LMPXS can provide a maximum modulation rate up to 100 Mbps which is expected to significantly improve the data rate of XCOM.

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1. Introduction

X-ray communication (XCOM) was proposed by Keith C. Gendreau at the Goddard Space Flight Center in 2007 and has the potential to satisfy the communication demands of several specific wireless channel environments and accomplish continuous communication and precise navigation anytime and anywhere [1].

XCOM uses an X-ray beam as the signal carrier to wirelessly transmit data in outer space. The X-ray beam with energy higher than 10 keV can transmit without attenuation through an environment with an atmospheric pressure below 10^{-3} Pa (attenuation length > 1.88×10^{8} m). Hence, the XCOM system can potentially provide a stable deep space communication link with high data rates at low power. X-ray has an exceedingly high frequency which allows XCOM to theoretically provide significantly large communication bandwidths. Porter [2] determined that the data rate can reach 40 Petabits/s per X-ray link by use of on–off keying modulation. The XCOM system has spawned many exciting applications. During spacecraft reentry and vehicles' hypersonic flight, the shock wave formed in front of the vehicle will compress and heat the air and make air molecules become dissociated and ionized. Thus, the plasma sheath is created thereby blocking the radio frequency (RF) communication by absorption and reflection which seriously affecting the safety of these vehicles. The modulated X-ray beam can surmount the plasma sheath because X-ray has an ultra-high frequency [3,4]. XCOM can also penetrate the RF shielding due to the penetrating characteristics of the X-ray beam. The XCOM system facilities have smaller size, weight, and power than RF and laser communication facilities; thus, these facilities can save on the limited spacecraft resources.

The Intensity Modulation/Direct Detection (IM/DD) system is a feasible solution for XCOM based on the current X-ray detection technology. The IM/DD XCOM facility consists of a modulated pulsed X-ray source (MPXS), a high time resolution X-ray detector [5–7], and necessary electronics system. Dr. Gendreau [8–10] designed an MPXS based on the pulse signal conversion of ultraviolet light to X-ray. The MPXS consists of a modulated ultraviolet emitter, a metal cathode, an electron multiplier, an electron accelerating cavity and an anode metal target. The modulated ultraviolet light pulses are converted into electron pulses by the metal cathode, the electron pulses are amplified by the multiplier, and the electrons generated by the multiplier are accelerated by the electric field. The accelerated electrons bombard the anode metal target, producing modulated X-ray pulses. The XCOM experiment was conducted by Dr. Gendreau in a 600 m vacuum beamline using the IM/DD facility; the system's communication rate of 50 kbps was attained. Zhao et al. [11] proposed an IM/DD XCOM system based on a grid-controlled X-ray source and realized a communication rate of 64 kbps in a 6 m vacuum pipeline. The structure of the grid-controlled X-ray source is similar to the conventional X-ray tube, and the difference is that a grid electrode is added near the hot cathode. Whether the

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https://doi.org/10.1016/j.nima.2018.01.031
Received 26 May 2017; Received in revised form 14 December 2017; Accepted 10 January 2018
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electrons produced by the cathode can pass through the grid electrode and be accelerated by the accelerated electric field is dependent on the potential of the grid electrode. Therefore, it is possible to realize the X-ray modulation by modulating the potential of the grid electrode.

The modulation rate represents the amount of binary that MPXS can transmit per second which is a critical factor that affects the communication rate of the XCOM system. However, all of the existing MPXSs cannot produce a high repetition rate, short pulse width, and high brightness modulated X-ray pulse. The low repetition rate and wide pulse width of the existing pulsed sources limit their modulation rate. In the case of high-speed signal transmission, if the MPXS brightness is too low to ensure that each pulse contains at least one photon, the information cannot be completely transmitted. Therefore, in order to realize high-speed X-ray signal emission, a new type of pulse source with a higher modulation rate and higher brightness is required.

2. Laser-MPXS

A MPXS was proposed based on the laser-to-X-ray conversion. It can output the X-ray pulse with a high repetition rate, short pulse width, and high brightness. An IM/DD XCOM system based on the proposed laser-MPXS (LMPXS) is shown in Fig. 1(a). A laser source and an intensity modulator are employed to generate a modulated laser pulse train with the high repetition rate. The optical pulse train is converted to the X-ray pulse train by the proposed LMPXS. The X-ray pulse is transmitted through the space environment and will be detected by an X-ray detector [12]. The electronic system eventually demodulates the signal received by the detector to restore the initial information.

The conversion process of the laser pulse to the X-ray pulse is shown in Fig. 1(b). X-ray pulses are produced by a four-step process, including photoelectric conversion, electron multiplication, electron acceleration, and electron-to-X-ray conversion. A transmission mode negative electron affinity (NEA) GaAs photocathode is employed to convert the laser pulse to an electron pulse. The electron pulse output from the photocathode is amplified by the micro-channel plate (MCP). Electrons output from the MCP are accelerated and focused by the accelerating electric field and focusing electrode in the electron accelerating cavity. The accelerated electrons eventually bombard the anode target, and producing modulated X-ray pulses.

The combination of the NEA GaAs photocathode and MCP, which has been used in low-level-light night vision systems [13], is selected to assure high conversion efficiency of the laser to X-ray and accomplish a high X-ray beam intensity output. The existing GaAs photocathodes and MCPs have been able to operate in the high frequency mode [14,15]. Disregarding the effect of the different structural designs of LMPXS, the conversion factor E_{source} of LMPXS in an ideal scenario can be approximately estimated as follows:

$$E_{source} = Q_{cathode} \times R_{MCP} \times G_{MCP} \times E_{anode}, \tag{1}$$

where $Q_{Cathode}$ is the quantum efficiency of the NEA GaAs photocathode, which indicates the conversion efficiency of laser photons and electrons. The $Q_{Cathode}$ value can commonly reach 20% [16]. R_{MCP} is the MCP's open area ratio, which indicates the ratio of the channel open area to the entire effective area of MCP. R_{MCP} is typically set at 60%. G_{MCP} indicates the multiplication gain of MCP, which can reach 10^4 [17,18]. E_{anode} is the electron-to-X-ray conversion efficiency of the anode target, which is approximately 8.3×10^{-3} [19]. Therefore, E_{source} is approximately 9.96, which means that approximately 10 X-ray photons will be emitted from LMPXS with one laser photon incident. Since the maximum output current of the commercially available MCPs are tens of microamperes which limits the flux of X-ray photons output from the LMPXS to approximately 10^{12} s^{-1} [18], Long-range space communication based on the single LMPXS is unrealistic due to its low transmitting power. Therefore, the signal transmitting array consisting of multiple LMPXSs and the X-ray concentrators are needed to make the long-range XCOM possible.

The width and repetition rate of the X-ray pulse output from the LMPXS directly determine the communication data rate of the proposed IM/DD XCOM system. The temporal characteristics of the LMPXS indicate the conversion performance of laser pulse to X-ray pulse; this performance directly affects the width and repetition rate of the output X-ray pulse and should be studied. Given that X-ray pulses are converted from laser pulses using the LMPXS by steps and accompanied by a series of changes in the signal pulse shape, the output X-ray pulse will be delayed and broadened, unlike the input laser pulse. Therefore, evaluating the temporal characteristics of the main LMPXS components is critical.

In the photoelectric conversion and electron multiplication processes, the time dispersion effect, which can be described by transit time spread (TTS), is significant. Therefore, it is necessary to analyze the temporal characteristics of the NEA GaAs photocathode and MCP. The electron pulse will be slightly broadened in the accelerating cavity owing to the existence of the space charge effect, which should be considered. By contrast, the time dispersion effect in the electron to X-ray process is insignificant and can be disregarded. The following sections evaluate the temporal characteristics of the photocathode and MCP. The holistic temporal characteristics of LMPXS, which refers to the temporal characteristics of the X-ray pulse train output from the LMPXS, will also be evaluated considering the space charge effects in the accelerating cavity; on this basis, the maximum modulation rate of LMPXS can be obtained. In addition, Saturation effects have a very important influence on the operation of MCP which result in the multiplication gain degradation. It limits the repetition rate of the MCP output electron pulses and reduces the maximum modulation rate of LMPXS, which will be taken into account in the analysis.

3. Temporal characteristic analysis of the photocathode

Laser with wavelength of 780–850 nm has been widely used for communication. It was selected as the excitation source in our scheme. NEA GaAs photocathode is a suitable photoelectric conversion device in our proposed LMPXS because of its high quantum at this wavelength [16,20]. The conventional NEA GaAs photocathode presents high quantum efficiency. However, its temporal response is slow, which cannot satisfy the requirements of ultrafast applications. Previous studies have provided two feasible solutions for the temporal response improvement: large exponential-doping (LED) NEA GaAs photocathodes [21] and field-assisted (FA) NEA GaAs photocathodes [22].

The candidate conventional, LED and FA NEA GaAs photocathodes were in transmission mode, and they all have the multilayer structure. As Fig. 2 shows, for conventional NEA GaAs photocathodes and LED NEA GaAs photocathodes, the multilayer structure consists of a glass substrate, Si_3N_4 anti-reflective layer, $Ga_{1-x}Al_xAs$ window layer, and GaAs absorption layer. In addition, the electron output surface is activated by O and Cs to make the surface barrier negative (i.e., the NEA state) [20]. For FA NEA GaAs photocathodes, except for the layers mentioned above, an Au–Zn electrode and an Ag film electrode are added to the multilayer structure. When the photoelectric conversion is carried out, the incident photons pass through the layers above the absorption layer. If the photons energy is larger than the energy band gap of GaAs, then the GaAs absorption layer will absorb the photons and produce electrons in the conduction band. These excited electrons will move toward the emission surface as a result of the diffusion and drift effect. The electrons will lose their energy by many scattering events during their transport process in the GaAs absorption layer, and several will eventually reach the emission surface. These electrons will be easily emitted into the vacuum because the surface barrier is negative, thereby providing the NEA photocathode with high quantum efficiency.

The LED NEA GaAs photocathode possesses a built-in electric field produced by the exponential hole doping method in GaAs absorption layer, whereas the FA NEA GaAs photocathode possesses an external electric field that accelerates the excited electrons, which can lower

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