A reliable sunlight communication system

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A sunlight communication system is proposed that uses $Sr_2Si_5N_8$: Eu^{2+} phosphors to concentrate sunlight signals in strong background light noise; thus, a wide spectrum sunlight communication system is converted into a narrow spectrum one. A communication method is proposed to enable compression to the dark line H- α (656.28 nm) spectrum. A 50% solar energy conversion efficiency is achieved with a 0.3 µs code delay, a 0.2 µs code rise time (20%–80%), and a 96% optical transmittance. Experimental results show that phosphors enhance the sunlight intensity 1.5 times with the same distance. This method has immense potential in future long-distance sunlight communication.

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Sunlight has been used for communication in ancient Greece and China. In 1810, Carl Friedrich Gauss used a pair of mirrors to direct a controlled beam of sunlight for heliograph communication^[1]. A sunlight phone was successfully developed by Bell in 1880. The sunlight signals were acquired by selenium crystals, and the communication distance reached 213 m. In 2014, Sunpartner Inc. invented the first fully integrated solar smartphone, which could realize visible light communication (VLC) by a solar cell^[2].

Sunlight communication is an ancient technology that has recently emerged to have potential application in space communication. Laser communication has been used to realize high-speed communication between artificial satellites. In 2001, Robinson et al. completed a laser communication experiment between the Advanced Data Relay and Technology Mission Satellite (ARTEMIS) and the Systeme Probatoire d'Observation de la Terre 4 (SPOT-4)^[3]. In 2008, Karafolas et al. realized a 5.56 Gbit/s high-speed communication between TerraSAR-X and the Near Field Infrared Experiment (NFIRE)^[4]. For high-speed indoor communications, Shemis et al. demonstrated an indoor free-space optical communication in the mid-L band by employing a 128 Gbit/s self-seeded quantum-dash laser generator⁵. In 2016, Li et al. realized 200 Mbit/s discrete Fourier transform spreading orthogonal frequency division multiplexing over a 2 m free-space transmission⁶. In 2017, Guo et al. proposed an adaptive multiple-input multipleoutput mode switching scheme for indoor VLC and realized a 50 Mbit/s communication with a bit error rate of 3.8×10^{-3} However, the quality of light communication is severely limited by the life and stability of the laser source.

To overcome these limitations, a novel sunlight communication system is proposed. The basic composition of the sunlight communication system is shown in Fig. 1. The solar beam is converged by lens A, which is collimated and contracted by lens B (D' > D''). The divergence angle of the transmitted beam is larger than that of the incident beam. If the ® diaphragm is used, the passed solar energy will decrease significantly, and the beam divergence angle will be compressed. According to non-ideal parallelism of sunlight, the received energy density with lens C is likely to be less than the background light energy density; thus, the transmission distance and signal-to-noise ratio (SNR) are limited.

There are two ways to increase the communication distance.

- 1. The spectral compression performance and shift increase the spectral purity so that a wide spectral band is transformed into a narrow spectral band.
- 2. The selected spectral segment is the dark line of the solar spectrum band, which may be the H- α band.

The selection criteria for the communication wavelength segment are as follows.

1. A simulation of the atmospheric transmission channel demonstrates that the flicker coefficient of the longer wavelength is less than the flicker coefficient of the shorter wavelength. Therefore, the spectrum segment



Fig. 1. Basic composition of sunlight communication system.

should select the red visible light, which is more conducive to the atmospheric transmission channel.

- 2. According to the Stokes photoluminescence principle, photons can be excited and emitted; the spectral range of the exciting photons is broadened so that there is enough energy for emitting photons.
- Hydrogen accounts for 71% of the solar atmosphere, helium accounts for 26%, and other gases account for 2%. Therefore, the dark absorption line of the solar spectrum is mainly the absorption of hydrogen atoms. According to the Baer end of the hydrogen atom, the characteristic line wavelengths are 410.12 nm, 434.01 nm, 486.07 nm, and 656.28 nm.

Therefore, the characteristic line wavelength of the hydrogen atom is 656.28 nm, which is selected as the sunlight communication wavelength.

A new approach using Sr₂Si₅N₈:Eu²⁺ phosphors converts high-energy photons to low-energy photons centered in the H- α spectrum band, thereby achieving spectrum down-conversion. The down-conversion compresses a wide sunlight spectrum into a narrow spectrum. Nitride phosphors are widely used in manufacturing white light emitting diodes (LEDs). The excitation band of the nitride phosphors $Sr_2Si_5N_8$ is distributed from ultraviolet light to yellow light, while the emission band is concentrated in the deep red light region at approximately $660 \text{ nm}^{\$}$. Moreover, the $Sr_2Si_5N_8$: Eu²⁺ material can regulate the proportion of the absorption constituents, which changes the wavelength of the output light in the range from green to yellow. Owing to the absorption of nitride, a quantum efficiency of over 80% can be achieved. However, the $Sr_2Si_5N_8$: Eu²⁺ phosphors selected in this study can be adjusted by the Eu^{2+} ion proportion, which can emit light in the H- α spectrum band⁹. The electronic configuration of the Eu^{2+} ion is $(Xe)(4f)^7(5s)^2(5p)^6$, and its ground state is $(4f)(^{8}S_{7/2})$. Recently, a new material CaMoO₄: Eu³⁺ compound has been demonstrated to show an intense characteristic red emission peak at 615 nm^[10]. A quantum efficiency of 100% can be achieved at different excitation wavelengths with almost negligible emissions at 656 nm. A down-conversion with a quantum efficiency close to 200% has also been demonstrated^[11,12]. The coordinate (x = 0.696, y = 0.365) in the CIE-1931 chromaticity diagram has a wavelength spanning from 610 nm to 630 nm, which does not overlap with the H- α spectrum band^[13]. Hence, CaMoO₄ compounds cannot be used for spectral compression. Additionally, according to the solar spectrum datasheet (NREL2011), more than half of the solar energy is concentrated on near-infrared and infrared wavelength regions. Assuming that infrared wavelengths are converted into the H- α spectrum band, the light energy in the H- α band will be increased significantly. A maximum up-conversion efficiency of 47.6% can be achieved from infrared wavelength to visible wavelength conversion^[14]. Likewise, Er^{3+}/Yb^{3+} co-doped thin films in silicon solar cells also can achieve an up-conversion¹⁵. Up-conversion can also be realized by a composite of Tm^{3+}/Yb^{3+} , Ho^{3+}/Yb^{3+} co-doped and $Tm^{3+}/Ho^{3+}/Yb^{3+}$

triply doped $\text{TeO}_2 - \text{Bi}_2\text{O}_3 - \text{ZnO} - \text{Li}_2\text{O} - \text{Nb}_2\text{O}_5$ (TBZLN) tellurite glasses, where the wavelength of the conversion output reaches 650 nm^[16]. Similar upconversion results are presented using composites of $\text{Sr}_2\text{CeO}_4:\text{Er}^{3+}/\text{Yb}^{3+[17]}$ and $\text{BaLa}_2\text{ZnO}_5:\text{Tm}^{3+}/\text{Yb}^{3+[18]}$. In general, up-conversion, i.e., spectrum conversion to the H- α spectrum band, is considered feasible. Nevertheless, this conversion efficiency is unsatisfactory^[19]. Consequently, conversion composites need to be further researched in the up-conversion of the solar spectrum.

In this work, we propose a sunlight communication system to overcome the difficulty of long-distance free-space light communication. $\rm Sr_2Si_5N_8:Eu^{2+}$ phosphors are introduced to compress the solar spectrum to the H- α band, which improves the quality of sunlight communication in strong background noise. The experimental results demonstrate that the solar energy conversion efficiency achieves 50%, the code delay is 0.3 µs, the code rise time (20%–80%) broadens, and the optical transmittance reaches 96%. The phosphors enhance the sunlight signal intensity 1.5 times without sacrificing the significant quality of the sunlight communication signal.

A contrast experiment is conducted to verify the feasibility of nitride phosphors for their application in sunlight communication. In the experiment, a white LED and sunlight are used as light sources.

The experiment demonstrates that the quality of the communication signal is influenced by the phosphors. The experimental setup is shown in Fig. 2. First, light communication is realized using a white LED. The LED is modulated by the non-return to zero (NRZ) code, and the light is converted by nitride phosphors. $Sr_2Si_5N_8$: Eu²⁺ composites are pasted onto K7 glass by epoxy glue at a 1:10 scale. An H- α optical filter and a photodetector are installed at the receiving side. The H- α filter is placed in front of the photodetector (OSI Optoelectronics PIN-100-YAG). The central wavelength of the H- α filter is 656 nm, and its bandwidth is 20 nm. The modulated light signal received by the detector is displayed by an oscilloscope (Lecroy 740Zi). A series of parameters are tested and recorded, including the code rise time, code delay, and optical transmittance. Moreover, a signal eye diagram is illustrated for signal quality assessment. We conducted an indoor experiment to eliminate other distractions in the background. Its results verify the phosphors' influence on the quality of the signals.



Fig. 2. Experimental setup for LED communication.

Additionally, a sunlight communication experiment was conducted outdoors to measure the spectrum conversion efficiency of the nitride phosphors in the H- α band. Moreover, this experiment verifies whether the sunlight signal intensity was enhanced by the phosphors. The experimental setup is shown in Fig. 3. First, the sunlight is converged by an energy-receiving antenna on the ground; this antenna tracks sunlight automatically to maximize the received energy. The converged light beam passes through an H- α optical filter and then propagates to an optical collimator by a fiber bundle. The H- α filter has a central wavelength of 656 nm \pm 5 nm. Subsequently, the conversion light is collimated through fiber bundles. The H- α optical filter, optical power meter, and photoelectric detector (Hamamatsu C7950-01) are installed at the receiving side. The converted light is modulated via the digital micro-mirror device (DMD, Texas Instruments D4100-7 XGA Kit). The enhancement ability of the sunlight intensity is measured by two of the same sunlight detecting configurations. The difference is the presence of nitride phosphors.

The $Sr_2Si_5N_8$: Eu²⁺ compound has covalency or a nephelauxetic effect with stronger energy levels, and the relaxation time is generated from the conversion. Therefore, it is critical to test the relaxation time of the communication system.

The power of the H- α band cannot be influenced by the phosphors introduced in the process of spectrum conversion. First, an absorptive test is performed on the H- α band. According to the experimental scheme, the source has to be a red LED (650–660 nm); the other test devices are the same as the ones used in the experiment described above. The measurement results of the absorptive test with different light intensities are 1.48 V, 1.52 V and 1.92 V, 2.0 V with corresponding transmittances of 97% and 96%, respectively. Therefore, the transmittance of phosphors for the H- α band is sufficiently high.

Table <u>1</u> shows the communication speed according to the relaxation time of light conversion. In this experiment, a white LED was used for pseudo-random code modulation with a 100 kbit/s current switch modulator. In the experiment with phosphors, the delta delay between the trigger signal and the measured signal was 6.0 μ s. In the experiment without phosphors, the delta delay between the modulated emitting signal and the measured signal was 5.7 μ s. We can conclude that there is a delay



Fig. 3. Experimental setup for sunlight communication system.

Table 1. Communication Delay Time and Time Edge

 Measurement

Experiment	With Phosphors (μs)	Without Phosphors (µs)	$\begin{array}{c} {\rm Results} \\ (\mu {\rm s}) \end{array}$
Delta delay	6.0	5.7	0.3
Rising edge (20%–80%)	1.3	1.1	0.2

difference of 0.3 μ s, which is derived from the relaxation time in photon conversion in phosphors. The rising edge measured is also approximately 0.2 μ s; therefore, the relaxation time is approximately 0.5 μ s, which is in accordance with the relaxation time $(10^{-8}-10^{-7} \text{ s})$ of the rare earth ion. Therefore, according to the broadening and delay of the signal, the communication speed is limited to 20 Mbit/s or less.

Figure <u>4</u> demonstrates the influence of nitride phosphors on the quality of the communication signal. Figure <u>4(a)</u> shows the eye diagram of the photoelectric signal without the phosphors' transition; Fig. <u>4(b)</u> shows the eye diagram of the photoelectric signal with the phosphors' transition. A comparison of these figures shows that the quality of the signals is indistinguishable.

In the sunlight communication experiment, as the sunlight intensity changes according to variations in the environment, large errors can be introduced when the sunlight intensity is measured at different communication distances. Therefore, the sunlight intensity is recorded by the optical power meter from the same distance at the same time. Two configurations are considered, one with phosphors and one without phosphors. The measured sunlight intensity is shown in Fig. <u>5</u>. The horizontal axis shows the measurement times with different sunlight intensities, and the vertical axis represents the reception



Fig. 4. Signal eye diagram (a) without phosphors and (b) with phosphors.



Fig. 5. Measured sunlight intensity values.

swing voltage. A significant enhancement of 1.5 times can be seen in the sunlight signal intensity when phosphors are used compared to when they are not. The enhanced intensity enables sunlight signals to be concentrated even in strong background light noise.

Considering the approach to limit communication speed, it is feasible that we collect sunlight and use nitride phosphors to compress the spectrum simultaneously before modulating the sunlight. In other words, the limitation of communication speeds can be avoided by an elaborate system design.

The optical epoxy glue and the phosphors are applied on a compound parabolic concentrator. During the course of this application, two problems that may affect the spectral regulation efficiency were found.

- 1. According to the principle of the compound parabolic concentrator, there is a greater amount of reflection when the light is concentrated closer to the focus; consequently, the phosphor material closer to the focus should be thicker than others in the coating procedure. However, the concentration and thickness of the phosphors are consistent across the entire surface of the concentrator. This can thus affect the efficiency of spectral regulation.
- 2. Owing to the curved nature of the compound parabolic concentrator, the spin coating approach cannot be used when coating with phosphors. Therefore, a manual coating of phosphors is applied, leading to unevenness. This is another factor that can affect the spectral regulation efficiency of the phosphors.

Figure <u>6</u> shows the experimental site and the system composition. The divergence angle of the system is optimized from 10 mrad to 0.2 mrad. The modulation mode of outdoor communication is on-off keying (OOK); the modulation rate is 20 kbit/s; the modulation pattern is a $2^6 - 1$ pseudo-random code. The bit error ratio of the eye diagram is 5.34×10^{-11} at a communication distance of 240 m. For potential applications such as remote communication in free space, the communication distance can be further improved by optimizing the divergence angle of



Fig. 6. Sunlight communication experiment and composition.

the system and measuring the minimum optical power and the loss in the optical channel.

The advantages of spectral regulation sunlight communication include its improved spectral purity, simple optical channel design, reduced modulation complexity, and reduced optical emission divergence angle. In the sunlight communication system, the noise affecting the received signal mainly includes background light noise, quantum noise, dark current noise, and thermal noise. The background light noise, which specifically affects the SNR of the received signal, cannot be ignored; the use of narrow band filters can significantly reduce background light noise in the receiving band.

The optical power link formula is given as follows:

$$P_{S} = P_{\rm in} \left(\frac{4\pi A_{R}}{\lambda^{2}} \right) \left[\frac{\lambda^{2}}{(4\pi L_{1})^{2}} \right] \left(\frac{4\pi A_{T}}{\lambda^{2}} \right) \rho_{F} \rho_{S}, \qquad (1)$$

where ρ_F is the gathering energy and transmission channel loss, ρ_S is the receiving channel loss, $P_{\rm in}$ is the concentered optical power, P_S is the receiving optical power, L_1 is the atmospheric transmission distance, A_R is the receiving aperture area, A_T is the effective aperture area, and λ is the optical wavelength.

The SNR formula is given as follows:

$$SNR = \frac{\overline{i}_s^2 R}{\overline{i}_n^2 R} = \frac{\overline{i}_s^2}{\overline{i}_n^2} = \frac{(RP_S)^2}{2eRP_{Be}B},$$
(2)

where P_{Be} is the total power of the background light radiation, P_S is the optical power of the received signal, e is the electronic charge, B is the bandwidth of the optical receiver, R is the response of the photodetector, \bar{i}_s is the average current of the received signal, and \bar{i}_n is the average current of the received noise.

The optical communication capability of ordinary solar communication and spectral regulation is compared. An explanation of several key parameters is shown in Table $\underline{2}$.

The transmission power of the solar spectrum regulation is 0.8 W, which is the energy already collected by the compound parabolic concentrator and then the power after spectral regulation. The divergence angle of the transmission beam is influenced by the design based on

Table 2. (Comparison of	f Ordinary	Communication	and Spectral	Regulated	Communication
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Parameter		Ordinary Comm.	Spectral-Regulated Comm.
Compound parabolic concentrator aperture	D_0	200 mm	200 mm
Loss of gathering and transmission channel	$ ho_F$	0.4	0.4
Transmission divergence angle	${m heta}_T$	10 mrad	$0.2 \mathrm{mrad}$
Transmission power	P_T	$10 \mathrm{W}$	$0.8 \mathrm{W}$
Loss of receiving channel	$ ho_S$	0.3	0.3
Transmitting antenna aperture	D_T	300 mm	300 mm
Communication bandwidth	В	$10 \mathrm{~MHz}$	$10 \mathrm{~MHz}$
Receiving field of view	$ heta_R$	10 mrad	10 mrad
Communication wavelength	λ	400 nm–700 nm	$655\pm5~\mathrm{nm}$
Receiving antenna aperture	D_R	300 mm	300 mm
Maximum photodetector response	R	0.6	0.6
Background total brightness	L_0	$100 \mathrm{W/m^2 \cdot gsr}$	$100 \mathrm{W/m^2 \cdot gsr}$
Power of receiving background light	$\boldsymbol{P}_{\mathrm{Be}}$	$1.11 imes 10^{-5}$	$3.4 imes 10^{-7}$
Communication distance	L_1	$210 \mathrm{~km}$	210 km
Signal to noise ratio	SNR	3.15 dB	64.19 dB



Fig. 7. Change in the SNR with respect to increasing distance.

the regulation. In Table 2, the SNR of ordinary solar communication is 3.15 dB for a transmission distance of 210 km, and the SNR can reach 64.19 dB after spectral regulation.

As the distance increases, the SNR changes, as shown in Fig. 7. The received noise is mainly background light noise, and the total input brightness of the near-surface sky is 100 W/m² · gsr, resulting in the background light power of the receiver being fixed with the distance. Therefore, it can be seen that the communication links with a distance of 110 km have SNRs of 75.31 dB and 14.38 dB, respectively; the two communication links are reliable, and the error is relatively small. As the distance increases, the SNR decreases rapidly. The SNRs of the communication links with a distance of 4100 km are

13.07 dB and -48.08 dB, respectively. The communication link with spectral regulation can function reliably, and the error is relatively small; the communication link without spectral regulation has not been established at all.

In summary, we propose a feasible solution to address the difficulty of long-distance sunlight communication. $Sr_2Si_5N_8$: Eu²⁺ phosphors are introduced to compress the solar spectrum for a sunlight communication system. The phosphors achieve down-conversion by converting photons from high-energy to low-energy and then into H- α bands. The experimental results show that the phosphors improve system performance without sacrificing the significant quality of the sunlight communication signal. The solar energy conversion efficiency achieves 50%, the code delay is 0.3 μ s, the code rise time (20%-80%) broadens, and the optical transmittance reaches 96%. The signal eye diagram shows that the phosphors have little impact on signal quality. Additionally, the phosphors enhance the sunlight signal intensity 1.5 times. The spectral compression sunlight communication has immense potential for future space-vehicle-to-space-vehicle or space-vehicle-to-space-station communication.

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