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光纤中三角斯托克斯脉冲的受激布里渊散射慢光

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摘　要:采用龙格库塔法和特征线法对光纤中受激布里渊散射耦合方程组进行数值求解,研究斯托克斯脉冲的增益、能量和半高全宽对时延和脉冲展宽的影响.结果表明:三角脉冲的增益、能量和宽度对时延和脉冲展宽都有影响,最大时延随着脉冲能量的减小而增加.脉冲宽度越窄,时延会越大.优化三角斯托克斯脉冲的增益、能量和宽度,可以获得最大时延和小的脉冲形变.该研究可为光通信和传感器件设计提供参考.

关键词:光纤;受激布里渊散射;慢光;脉冲展宽;斯托克斯波
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SBS Slow Light of Triangular Wave Stokes Pulses in Optical Fibers

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Abstract: The coupled amplitude equations of stimulated Brillouin scattering in optical fibers are numerically solved with fourth-order Runge-Kutta formula and characteristics methods, the influences of gain, energy, and Full Width at Half Maximum (FWHM) of injected triangular wave Stocks pulses on time delay and pulse broadening are investigated. The results show that the time delay and pulse broadening depend on the gain, energy and FWHM of the triangular pulses. The maximum time delay increases with the injected pulses energy decreasing. Smaller FWHM of pulse induces larger relative time delay. The maximum time delay and less pulse broadening can be obtained by optimizing the gain, energy, and FWHM of injected triangular wave Stocks pulses. These results provide reference for designing novel optical communication or sensing components.

Key words: Optical fiber; Stimulated Brillouin scattering; Slow light; Pulse broadening;Stokes wave
OCIS Codes: 060.2270; 060.4370; 060.4510; 060.2310

0　Introduction

It is well known that all-optical buffer is the key technology for all-optical routers. Although optical Fiber Delay Line (FDL) is used to delay the optical signal, but it is difficult to tailor the delay time. In recent years, slow light operating in solid-state material at room-temperature was demonstrated extensively[1], this technology includes Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), Coherent Population Oscillations (CPO) and dispersive slow light (conversion/dispersion) (C/D), and optical fiber grating and so on. Herein SBS slow light has been paid much more

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attention due to its much more advantages, such as tunable operating at room temperature, compatibleness with optical communication system, sensitive to temperature or strain, etc[2,3].

Slow light via SBS was first proposed by Gauthier[4] in 2004, Researchers in Switzerland and America experimentally presented controllable slow light via SBS in optical fiber in 2005[5-6], respectively. Herraze et al.[7] increased the SBS gain bandwidth of single mode fiber from 40 MHz to 325 MHz by modulating the pump injection current with a Gaussion noise source. Then Zhu et al.[8] extended the bandwidth up to 12.6 GHz. Song et al.[9] achieved a bandwidth of 25 GHz by using a second broadened pump separated from the first one by the acoustic wave frequency, which made it possible to apply SBS slow light techniques to optical communication system with speed of dozens Gbit/s. M. D. Stenner et al.[10] presented techniques for designing pulses for linear slow-light delay systems and S. Chin et al.[11] experimentally demonstrated the effect of a proper shaping of the temporal envelope of isolated pulses in slow-light systems based on stimulated Brillouin scattering in optical fibers. Our group[12] reported the influence of super-Gaussion shaped pulses on SBS slow light in optical fibers and that time delay and pulse broadening depend on shape, energy and duration of injected pulses, the maximum time delay and less pulse broadening can be obtained from optimizing shape of super-Gaussion shaped pulses.

In this paper, the three coupled amplitude equations of SBS in fibers are solved by fourth-order Runge-Kutta formula[13] and characteristics line method[14-15]. The influences of the gain, energy, and the Full Width at Half Maximum (FWHM) of injected triangular wave Stocks pulses on time delay and pulse broadening are studied, some interesting results are obtained and the mechanism is analyzed.

1 Theory analysis

Supposed the Stokes wave transmitting along the $+z$ direction, and the pump light along the $-z$ direction in optical fiber, by using the slowly varying envelope amplitude approximation, the three coupled amplitude equations which quantitatively describes the interaction between the pump and Stokes fields through an acoustic wave, can be expressed as[16-17]

$$\begin{cases}-\dfrac{\partial E_{\mathrm{p}}}{\partial z}+\dfrac{n_{\mathrm{fg}}}{c}\dfrac{\partial E_{\mathrm{p}}}{\partial t}=-\dfrac{\alpha}{2}E_{\mathrm{p}}+\mathrm{i}g_2E_{\mathrm{s}}\rho\\ \dfrac{\partial E_{\mathrm{s}}}{\partial z}+\dfrac{n_{\mathrm{fg}}}{c}\dfrac{\partial E_{\mathrm{s}}}{\partial t}=-\dfrac{\alpha}{2}E_{\mathrm{s}}+\mathrm{i}g_2E_{\mathrm{p}}\rho^*\\ \dfrac{\partial\rho}{\partial t}+\left(\dfrac{\varGamma_{\mathrm{B}}}{2}-\mathrm{i}\Delta\omega\right)\rho=\mathrm{i}\dfrac{g_1}{\eta}E_{\mathrm{p}}E_{\mathrm{s}}^*\end{cases}\tag{1}$$

where E_{p} and E_{s} are the amplitudes of pump wave and Stokes wave respectively, ρ is acoustic matter-density field, c is the velocity of the light in vacuum, α is the loss coefficient of the fiber, $\varGamma_{\mathrm{B}}$ denotes the FWHM of the gain spectrum related to the phonon lifetime T_{B} as $\varGamma_{\mathrm{B}}=1/T_{\mathrm{B}}$, $\Delta\omega=(\omega_{\mathrm{p}}-\omega_{\mathrm{s}})-\varOmega_{\mathrm{B}}$ is the angular frequency deviation from the center of the SBS gain, also called frequency detuning, $\varOmega_{\mathrm{B}}$ is the Brillouin frequency, ω_{p} and ω_{s} are the angular frequency the pump wave and Stokes wave, $g_1=\gamma\varepsilon_0\varOmega_{\mathrm{B}}/(4v_{\mathrm{a}}^2)$ is the coupling coefficient between pump wave and Stokes wave, $g_2=\gamma\omega_{\mathrm{p}}/(4cn_{\mathrm{f}}\rho_0)$ is the coupling coefficient between pump wave (Stokes wave) and acoustic field, $\eta=cn_{\mathrm{f}}\varepsilon_0/2$, γ is the electrostrictive constant of the fiber, ε_0 is the vacuum permittivity, ρ_0 is the unperturbed density of medium, n_{f} is the phase refractive index and n_{fg} is the group refractive index without SBS.

Setting that pump wave is continuous wave and Stokes field is sufficiently weak, according to the weak signal theory,the group index is the function of frequency, and can be written as[14]

$$n_{\mathrm{s}}(\omega)=n_{\mathrm{f}}+\frac{cg_0I_{\mathrm{p}}}{\omega}\,\frac{\delta\omega/\varGamma_{\mathrm{B}}}{1+4\delta\omega^2/\varGamma_{\mathrm{B}}^2}\tag{2}$$

where I_{p} denotes the optical intensity of pump wave, $\delta\omega$ is the margin between the angular frequency of Stokes pulse and the center angular frequency of the gain bandwidth, $g_0=\dfrac{\gamma_{\mathrm{e}}^2\omega_{\mathrm{p}}^2}{n_{\mathrm{g}}v_{\mathrm{B}}c^3\rho_0\varGamma_{\mathrm{B}}}$ represents the gain factor which is associated with the material physical properties, v_{B} is the velocity of acoustic wave, n_{g} is the group index of the fiber mode.

Time delay T_{d} is defined to describe arrival time difference of output Stokes pulse peaks between when

SBS happens and when SBS doesn't happen. Relative time delay $T_{\mathrm{rd}}=T_{\mathrm{d}}/T$, where T is the FWHM of the injected Stokes pulse, pulse broadening factor B represents proportion of input Stokes pulse FWHM and output Stokes pulse FWHM. According to the weak signal theory, time delay T_{d} and B are taken the form[18]

$$T_{\mathrm{d}}=G/\Gamma_{\mathrm{B}} \tag{3}$$

$$B=\sqrt{1+\frac{16\ln 2}{T^2\Gamma_{\mathrm{B}}^2}G} \tag{4}$$

where $G=g_{\mathrm{B}}I_{\mathrm{p}}L$ is the weak signal gain parameter, L is the fiber length. Real gain denotes how much the pump wave energy is coupled to the Stokes wave energy and take the form

$$G_{\mathrm{r}}=\log(P_{\mathrm{out}}/P_{\mathrm{in}}) \tag{5}$$

where P_{out} and P_{in} are peak energy of the output and input Stokes wave, respectively. If the shape of output pulse is distorted from the input, they mean the average energy of the pulses.

We assume that injected Stokes pulse is Triangle wave function which can be expressed as

$$U(t)=\mathrm{trimf}\left(-\frac{T}{2},0,\frac{T}{2}\right) \tag{6}$$

where $U(t)$ is normalized amplitude, T is the FWHM of the injected Stokes pulse. The triangle pulse is shown in Fig.1.

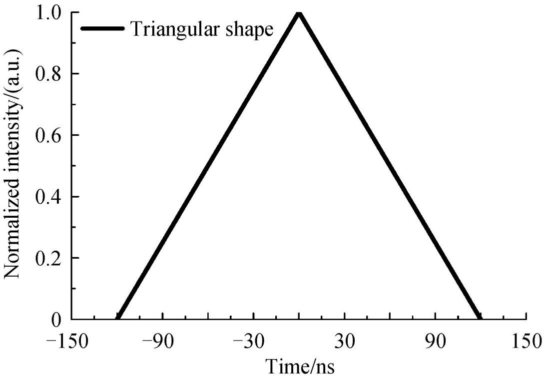


Fig.1 Injected Triangular wave

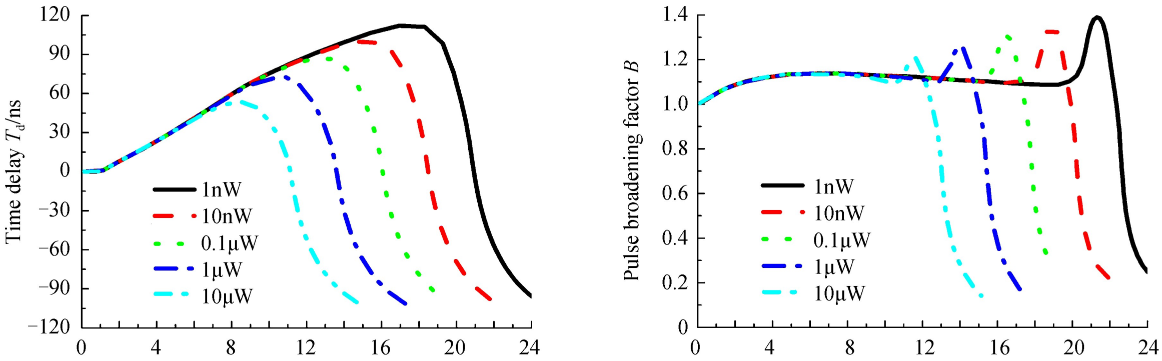
By using the Slowly-Varying Envelope Approximation (SVEA) for both pump and Stokes fields, the values of ρ can be obtained at a given time by solving Eq. (1) with Fourier transformation and inverse Fourier transformation[15,19]. Then Eq. (1) are transformed into single variable partial differential equations by using characteristics line method. At last , substituting the value of ρ to the single variable partial differential equations, the values of E_{p} and E_{s} can be calculated at next time by using the fourth-order Runge-Kutta formula. We set these results as the initial value to calculate the value of ρ at next time. Repeating above steps, the output Stokes pulse at anytime can be obtained.

2 Numerical results and discussion

In our numerical simulations, we assume that the pump wave is a continuous wave without frequency chirp, the triangular wave Stokes pulse is on the SBS line center ($\delta\omega=0$), and setting the parameters as follows: $L=50$ m, $n_{\mathrm{g}}=1.45$, $\alpha=0.2$ dB/km, $A_{\mathrm{eff}}=50\ \mu\mathrm{m}^2$, $\Gamma_{\mathrm{B}}/2\pi=40$ MHz, $\Omega_{\mathrm{B}}/2\pi=10.8$ GHz and $g_{\mathrm{B}}=5\times10^{-11}$ m/W, The pump light power is 20mW, the wavelength of Stokes wave $\lambda=1\ 550$ nm.

2.1 Influence of triangular wave Stokes pulse slow light on input power

The curves of time delay and broadening factor of triangular wave Stokes pulse vs the gain for different power are shown in Fig.2 (a) and (b), respectively. From Fig.2(a), it can be seen that the maximum delay time and the corresponding gain at which maximum delay time generates are reduced with the increasing of input power, but pulse delays are substantially equal before the gain reaches to the saturation. This is because the pulse with larger power gets saturated at smaller gain, and the time delay and gain approximately proportional relationship in the small signal region. We can see from Fig.2(b), when the gain is less than the gain saturation, pulse broadening factor is basically around at 1.1. But with the gradual increasing of the gain, the pulse broadening factor with the largest power pulse firstly appears a peak value, and more peaks appear with power decreasing, the height of these peaks is larger with the gain increasing. This shows that the average high intensity pulse gets more easily saturated.



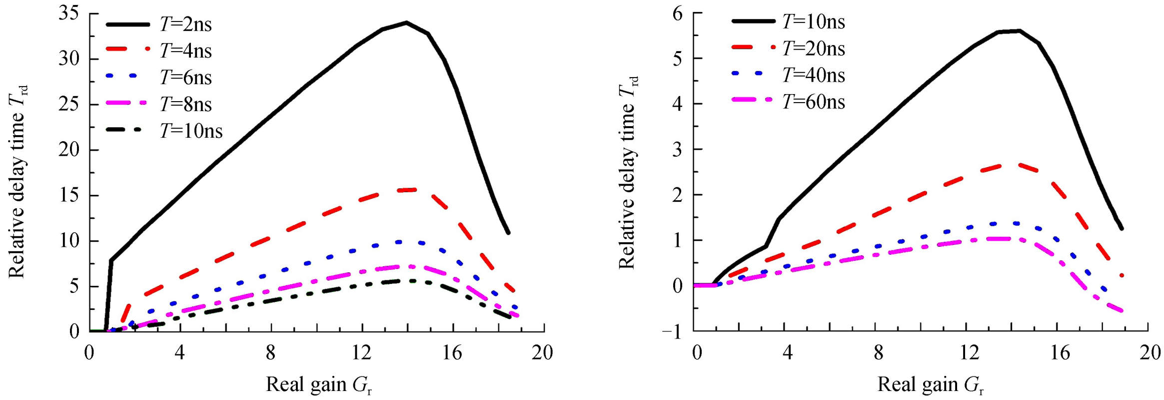
(a) Time delay

(b) Boradening factor

Fig.2 Time delay and broadening factor of output Stokes pulse varies with the gain for different power

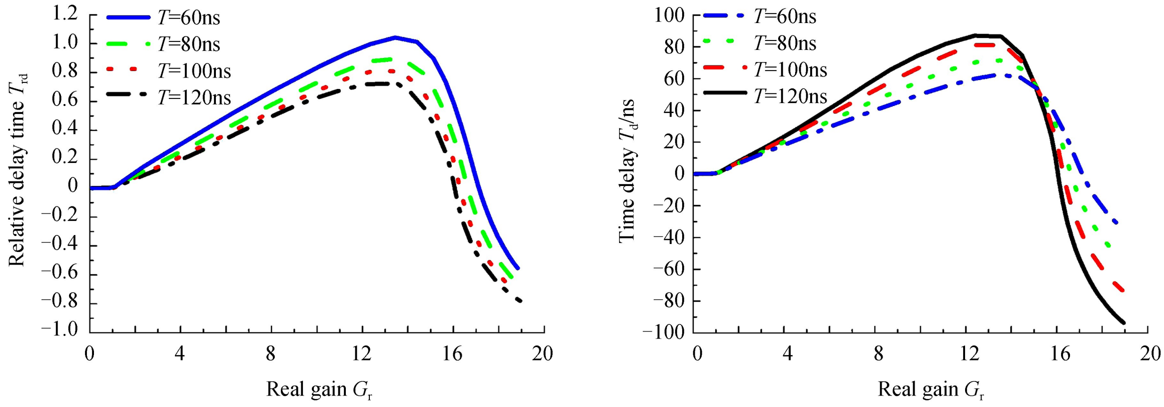
2.2 The relative delay time for different width of the pulses

Fig.3 shows the relative delay time T_{rd} varies with the gain for pulses with different FWHM, where the input power is 0.1 μW. It can be seen that the delay time increases to reach a maximum value and then decreases with the increasing of the gain, even become negative (so called fast light phenomena) at larger gain. Relatively larger delay time is obtained for smaller FWHM pulse, for example, if FWHM is less than 60 ns, the delay time of several times of pulse width is obtained, but when FWHM is less than 4 ns, the delay time of tens times of pulse width is easily obtained, and the gain corresponding with maximum delay time also increases gradually. This is because for the pulse with same peak power, the time domain energy is smaller for the pulses with smaller FWHM, thus keeping the pump power is constant, the higher saturated energy is required so as to the saturate gain increase gradually.



(a) T_{rd} for T from 2 ns to 10 ns

(b) T_{rd} for T from 10 ns to 60 ns



(c) T_{rd} for T from 60 ns to 120 ns

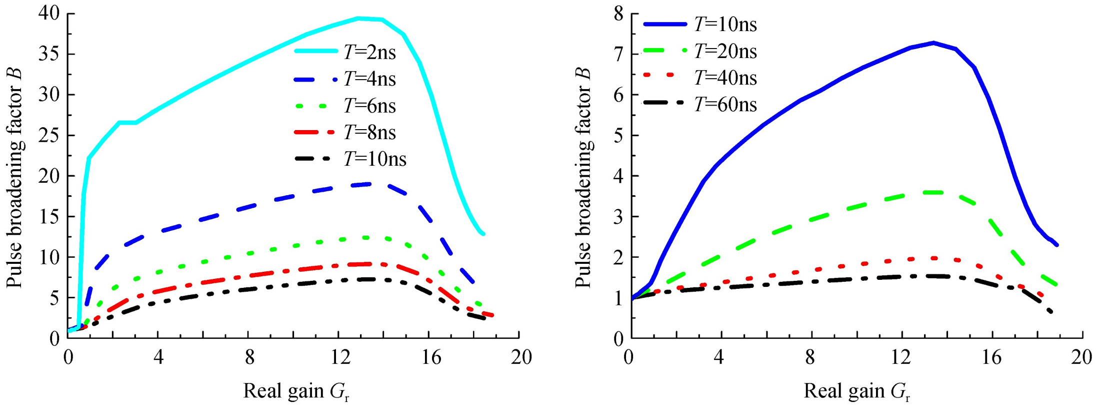
(d) T_{rd} for T from 60 ns to 120 ns

Fig.3 Relative delay time T_{rd} and time delay T_d of injected Stokes pulse varies with the gain for pulses with different FWHM

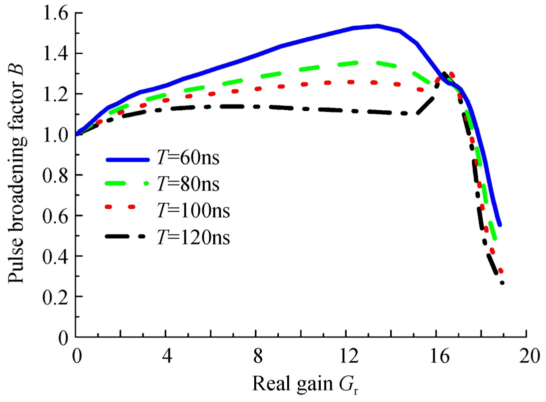
2.3 The pulse broadening factor *B* for different width of the pulses

Fig.4 shows the curves of the pulse broadening factor B varying with the gain for pulses with different

FWHM. It can be seen that the pulse broadening factor B increases with the decreasing of FWHM. When FWHM is less than 4ns, pulse broadening factor B is greater than 10, which is because narrow pulse has high peak power and strong nonlinear interaction. It also shows that the pulse broadening factor of small FWHM pulse is very different from those of more than 100 ns, but its curves is similar to that of Gaussian pulse. Because when the pump pulse energy decreases, the loss increases with the FWHM decreasing, thus the energy of the backward pulse with large the FWHM is higher, so the backward pulse is broadened, and there is a steep front pulse due to pulse compression.



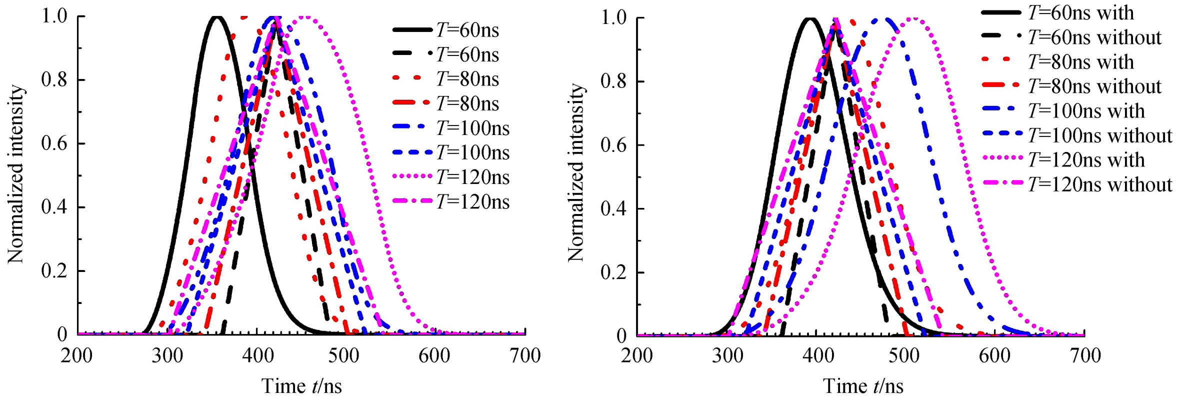
(a) T from 2 ns to 10 ns (b) T from 10 ns to 60 ns



(c) T from 60 ns to 120 ns

Fig.4 Pulse broadening factor B varies with the gain for pulses with different FWHM

Fig.4 (c) indicates that when FWHM=120 ns, the pulse broadening factor is basically around 1.0, and gradually decreases then gradually increases to the peak at the gain of about more than 13.5, then decrease rapidly to below 1.0, which means the pulse is compressed. When the FWHM is from 100 ns to 80 ns, the pulse broadening factor corresponding to the maximum delay is less than 1.2. This is also showed in Fig.5.



(a) G_r=5 (b) G_r=13

Fig.5 Waveform of output Stokes pulse with or without SBS at different gain

Fig.5 shows the normalized waveforms of Stokes pulses for four different pulse width with SBS and without SBS at the gain (a) $G_r=5$(far from the gain saturation) and (b)$G_r=13$(close to gain saturation), respectively. It can be seen from Fig.5 (a) that the leading and trailing edges broaden for those pulses with SBS with the increase of FWHM, so according to Eq. (2), the velocity difference of the leading and trailing edges increase and the more power contributes at leading edge, so the energy of the triangular pulses with the same peak value increases with the FWH M increasing, the energy of the trailing edge is relatively lower due to the smaller gain, this leads to reduce the pulse broadening factor, and makes pulse broadening factor is close to 1 before Stokes pulses achieve the gain saturation.

When the gain gradually increases to the gain saturation, the energy of the trailing edge increases to broaden the triangular pulses, then pulse broadening factors increase with the increase of FWHM as shown in Fig.5 (b). When the gain increases beyond the small signal range, there is a major distortion waveform. The frontiers of the pump wave pulse and Stokes pulse encounter together and lead to SBS happen, which lead to the asymmetric of the leading edge and the trailing edge of output Stokes pulse as mentioned above. This process also includes the pumping loss, pulse deformation distortion and time delay.

3 Conclusion

According to the above numerical simulation and theory analysis, we conclude that the gain, energy, and the FWHM of injected triangular wave Stocks pulses have great influence on time delay and pulse broadening. The larger time delay and less pulse broadening can be obtained when the gain value is 12, the maximum time delay increase with the decreasing of injected pulses energy. For triangular pulses with different width, greater relative time delay can be obtained for pulses with smaller FWHM. These results provide reference for designing novel components for optical communications or optical sensing.

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