

ASSESSMENT OF TARGET DETECTION ABILITY FOR LASER FUZES IN FOG CONDITIONS

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Abstract: The article presents a method to evaluate the target detection efficiency of laser fuzes operating in foggy conditions. The evaluation model is built from: the distance equation of the laser system, the attenuation of the beam in two-way propagation, the disturbances affecting the system; the signal to noise ratio SRN has determined the detection probability of the receiver. The model was used to evaluate with wavelengths: 850 nm, 1000 nm and 1550 nm, when propagating in three different bad weather conditions. The results show that the most effective detection of the target when using a wavelength of 1550 nm in visibility in haze and mist conditions (visibility $V > 500$ m). In fog conditions (visibility $V < 500$ m), the above three wavelengths provide the same detection efficiency. The article provides the method and instructions for choosing the wavelength of the laser fuze.

Keywords: Laser fuze; Laser wavelength; Atmospheric attenuation.

1. INTRODUCTION

The laser fuze performs short-range target detection (the detection distance usually less than 20 m) and controls the timely detonation of ammunition based on the detected target information [1, 2]. Application of laser fuzes has played an important role to improve the fire efficiency of anti-aircraft missiles, but also gives problems. With anti-aircraft fuzes, the attenuation of the laser beam in fog scattering conditions is a serious problem [3].

In the design of laser fuzes, the most common APD avalanche photodiodes includes: Nd:YAG with a wavelength of about 1550 nm and a silicon-based APD (Si-APD) with a wavelength of about 1000 nm and 850 nm with many advantages in terms of transmitting power, receiver sensitivity,... Therefore, this paper focuses on evaluating the effectiveness of target detection on the basis of these wavelengths.

Concerning target detection in poor weather, Zhang and Wang studied the feedback signals of continuous-wave and pulsed laser fuze in clouds, but not mention other conditions such as fog [4, 5]. In addition, Winker and Poole simulated the backscattered cloud signal for near-infrared lasers [6]. Srivastava calculated the backscattering efficiency of cloud aerosols by near and far infrared lasers [7]. However, these papers are not applicable to short-range target detection because these results are focused on laser sensing systems with farther detection distance (usually hundred meters to hundred kilometers).

Fog, heavy snow, and extreme rain are the primary weather types that can affect the laser systems. The large attenuation values in heavy fog can reduce the availability of laser systems. The laser is subject to the following basic effects during target detection procedure: (1) when a target is present, absorption and scattering due to water vapor particles attenuate the beam energy entering the receiver of the fuze. The elements scattering back towards the receiving lens contribute background noise, which reduces the SNR of the receiver; (2) if the target is not present, the backscattered cloud and fog will produce a false feedback laser signal that a target will be falsely detected (false

alarm). Therefore, the intensity of the target feedback signal when there is a target is evaluated by the probability of detecting the target P_d . The intensity of the backscatter feedback signal from clouds and fog when there is no target is evaluated by the average false alarm rate FAR [8].

When choosing a transmission wavelength with appropriate requirements, atmospheric attenuation will not be an ominous factor; thereby improving the detection ability of the laser fuze. The article clarifies the effects of laser wavelength on the attenuation when propagating in different weather conditions.

2. LASER FUZE PERFORMANCE

2.1. The attenuation of laser power through the atmosphere

The laser fuze determines the distance from the missile to the target that processes the signal to give the command to detonate the warhead at a predetermined distance. When the missile approaches the target, the laser pulses from the emitter block, after encountering the target surface, reflect and enter the receiver.

Considering the influence of other factors in the motion of the target and missile on the propagation and reflection of the beam that has been resolved and the plane of reflection is perpendicular to the direction of propagation of the beam. The laser range equation is the basis for designing the system and evaluating the performance of the system. The laser fuze of the anti-aircraft missile works at a short range to the target; the target size is much larger than the beam size and has a Lambertian reflectance distribution, the distance measurement equation is determined by [9]:

$$P_r = \frac{P_t \cdot \tau_t \cdot \tau_r \cdot \rho \cdot D^2 \cdot \tau_a^2}{4 \cdot R^2} \quad (1)$$

where: P_r - Power received in watts; P_t - Power transmitted in watts; τ_t - Transmitting optics efficiency; τ_r - Transmitting optics efficiency; ρ - Reflectance; D - Entrance diameter in meters; τ_a - Atmospheric transmission factor (one way); R - Range in meters.

The atmospheric effects limit the performances of laser fuze systems as the laser pulse propagates through the air. Many complex phenomena as turbulences, beam broadening or intensity variations occur and perturb the laser beam. The gases and particles in the air absorb and reflect the laser light. This creates a loss modelled by Beer-Lambert law which represents the attenuation of the beam power with the travelled distance. Assuming a constant atmospheric extinction coefficient, the law reduces to a form [10]:

$$\tau_a = \exp(-\sigma \cdot R) \quad (2)$$

where: τ_a - Transmittance at range R ; σ - Attenuation of total extinction coefficient (per unit length) (m^{-1}).

Figure 1 shows a plot of the atmospheric attenuation as a function of visibility [11]. The top shows the weather conditions that correspond to the visibility. The definition of visibility or visual range is the distance that light decreases to 2% of the original power, or qualitatively, visibility is the distance at which it is just possible to distinguish an object against the horizon. The relationship between visibility and the amount of atmospheric attenuation is inverse obviously. Typical margins for atmospheric

attenuation can run from 30 dB to 50 dB at 500 m range which corresponds to handling attenuation up to 60 to 100 dB/km. The primary weather that can cause problems for these short ranges (< 500 m) is fog and heavy snow.

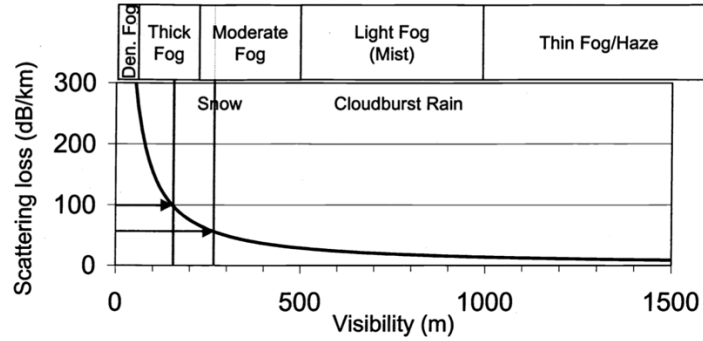


Figure 1. Amount of atmospheric attenuation as a function of visibility.

Since the laser pulse travels twice the distance to the target before reaching the receiver, it is affected by [11]:

$$T_a = \tau_a^2 = \exp(-2 \cdot \sigma \cdot R) \quad (3)$$

Attenuation of total extinction coefficient σ depends on wavelegths can be calculated [12]:

$$\sigma = \frac{3.91}{V} \left(\frac{\lambda}{0.55} \right)^{-q} \quad (4)$$

where V denotes the cloud visibility, λ denotes the laser wavelength, q is the empirical coefficient.

From [11, 12], the empirical coefficient q , which is expressed by:

- $q = 1.6$ for high visibility $V > 50$ km;
- $q = 1.3$ for average visibility $6 \text{ km} < V < 50 \text{ km}$;
- $q = 0.585 \times V^{1/3}$ for low visibility $V < 6 \text{ km}$;
- $q = 0.16 \times V + 0.34$ for haze visibility $1 \text{ km} < V < 6 \text{ km}$;
- $q = V - 0.5$ for mist visibility $0.5 \text{ km} < V < 1 \text{ km}$;
- $q = 0$ for fog visibility $V < 0.5 \text{ km}$.

The attenuation coefficient σ has contributions from the absorption and scattering of laser photons by different aerosols gaseous molecule the atmosphere. The effects of scattering, therefore, dominates the total attenuation coefficient. The type of scattering is determined by the size of the particular atmospheric particle with respect to the transmission laser wavelength. Transmission attenuation, hence, depends mainly on wavelength laser beam.

2.2. Detection efficiency of laser sensor

The target detection efficiency of the laser fuze is characterized by the probability of detecting P_d . The detection probability is determined by comparing the Signal-to-Noise SNR with the Threshold-to-Noise Ratio (TNR).

The SNR is an important parameter to evaluate the detection efficiency of a laser

sensor. As can be seen from Eq. (1), several factors influence the performance of laser systems. Generally, the laser range equation is often expressed in the form of SNR [12]:

$$SNR = \left(\frac{P_r}{NEP} \right)^2 = \left(\frac{P_t}{NEP} \right)^2 \cdot \left(\frac{\tau_t \cdot \tau_r \cdot \rho \cdot D^2 \cdot \exp(-2 \cdot \sigma \cdot R)}{4 \cdot R^2} \right)^2 \quad (5)$$

where: P_r – Power received in watts; NEP – Noise equivalent power in watts, and it is interpreted as the standard deviation for the Gaussian distribution.

Many noise sources affect the distance measurements in the receiver as background noise, detector dark current, thermal noise and photon shot noise. These include noise generated by the system (electronic components, cabling, etc.), statistical changes created by the light reaching the detector, and stray light (i.e. sunlight). Anything that is not at a temperature of 0 K radiates photons. Since a detector is not perfectly cold, it will generate noise. More than 15 parameters have to be estimated to be able to simulate the noises. Consequently, in order to provide a more simplified model, a general factor handles the noise. Indeed, if all these noises are unknown, their combination yields a Gaussian distribution. Furthermore, the standard deviation of this Gaussian distribution has the value of the Noise Equivalent Power (NEP). As the power of the sent pulse is known, it is possible to modify the Signal to Noise Ratio of the received signal.

Noise equivalent power (NEP) is a measure of the sensitivity of a photodetector or detector system. NEP is combined together by the noise in detector and preamplifier:

$$NEP = \sqrt{NEP_{\text{detector}}^2 + NEP_{\text{preamp}}^2} \quad (6)$$

where: NEP_{detector} – Noise equivalent power of detector

NEP_{preamp} – Noise equivalent power of preamplifier

The laser system measures the distance to the target through processing the laser signal entering the receiver lens. The receiver lens focuses the collected light onto a small optical detector. The optical detector converts the optical signal into an electrical signal. The most commonly optical detectors are avalanche photodiodes (APDs) with a wavelength range from 300 nm to 1700 nm. This article uses silicon-based avalanche photodiodes (Si-APD) sensitive in the wavelength from ≈ 450 nm to 1000 nm; using two emission wavelengths 850 nm and 1000 nm. For wavelengths up to about 1500 nm, an Indium-Gallium-Arsenide APD (InGaAs-APD) should be used.

An important parameter for minimizing the noise at the receiver is the bandwidth B of the electronics following the optical receiver. With a too large bandwidth, too much noise is admitted in the system. With a too narrow bandwidth, parts of the received signal are modified or suppressed [13]. The noise equivalent power of APD (NEP_{detector}) is calculated by:

$$NEP_{\text{detector}} = NEP_{\text{Hz}} \cdot \sqrt{B} \quad (7)$$

where NEP_{Hz} is noise equivalent power of APD; and B is noise bandwidth.

The noise equivalent power of preamplifier (NEP_{preamp}) is [14]:

$$NEP_{\text{preamp}} = \sqrt{\frac{4kTBN}{R_L R^2 e s}} \quad (8)$$

where: k - Boltzmann's constant; N - Noise factor of the preamplifier;

R_L - The load resistor = $1/2\pi BC$; C - Capacitance of the APD; T - The temperature of circuit (in K degrees); R_{es} - The responsibility of ADP.

Probability of detection P_d is another important parameter, based on pulse detection in white noise using a matched filter, the probability of detection is:

$$P_d = \frac{1}{2} + \frac{1}{2} \operatorname{erf} \left(\frac{\text{SNR} - \text{TNR}}{\sqrt{2}} \right) \quad (9)$$

where P_d , $\operatorname{erf}(x)$ and TNR are probability of detection, error function and Threshold-to-noise ratio, respectively.

Threshold to noise ratio is given by:

$$\text{TNR} = \sqrt{-2 \ln(2\sqrt{3} \cdot \tau \cdot \text{FAR})} \quad (10)$$

where τ is laser pulse width; FAR is average false alarm rate = $P_{fa} \cdot \text{PRF}$; P_{fa} is single pulse false alarm rate; PRF is laser pulse repetition frequency.

The detection efficiency of a pulsed laser sensor is characterized by the detection range corresponding to the value of the SNR. Equations (1) to (10) show the relationship of the SNR to hardware parameters, weather conditions, and target characteristics.

3. SIMULATIONS AND RESULTS

The simulation has been developed to support future hardware device development and system engineering studies of laser fuze. Calculations are based on the requirement of detection probability P_d of 99% at an average false alarm rate of $\text{FAR } 10^{-4}/\text{s}$ over the operating range of laser fuze. The detection probability graph based on the SNR for different average false alarm rates FAR is shown in figure 2.

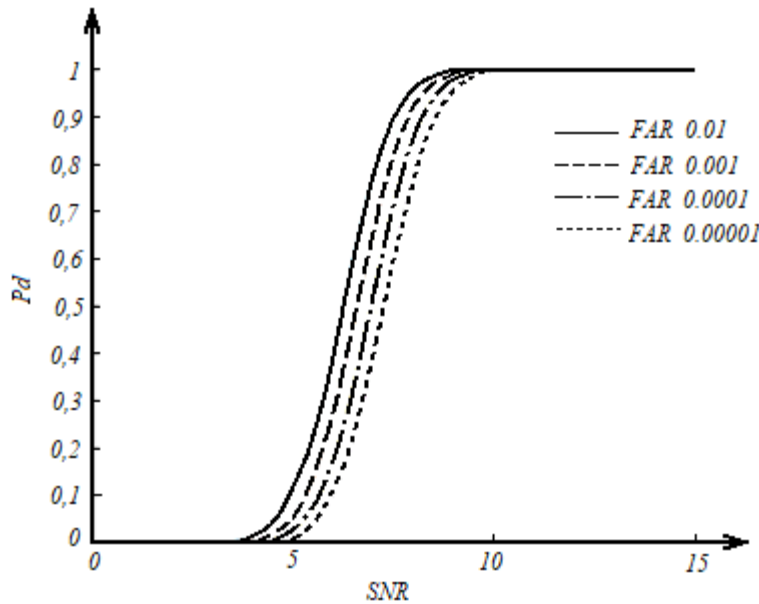


Figure 2. Probability of detection with FAR values.

According to the analysis results, as the FAR decreases, the required SNR value to get 99% detection probability will increase. This reduces the maximum detection range of the laser fuze.

In simulation calculations, using a Lambertian target with a reflectance of 0.2, the target surface is perpendicular to the propagating direction of laser fuze in a foggy environment. Bad weather conditions are considered in three cases: Haze ($1 \text{ km} < V < 6 \text{ km}$), Mist ($0.5 \text{ km} < V < 1 \text{ km}$), and Fog ($V < 0.5 \text{ km}$). The laser signal which is reflected from the target and/or scattered from the cloud enters the receiver lens with wavelengths of 850 nm, 1000 nm, and 1550 nm.

Table 1. Simulation Conditions.

Laser transmitted peak power (P_t)	50 W
Diameter (D)	0.04 m
The temperature of circuit (T)	300 K (25°C)
Noise factor of the preamplifier (N)	2
Pulse repetition frequency PRF	10 KHz
Pulse width (τ)	100 ns
The load resistor (R_{Load})	$1/2\pi BC$
Detector bandwidth (B)	35 MHz
Capacitance of the APD (C)	1 pF
The responsibility of ADP (R_{es})	9.4 A/W (Si-APD) 9 A/W (InGaAs-APD)
Noise Equivalent Power of preamplifier (NEP_{Hz})	10-14W/ Hz (Si-APD) 0.15×10-15W/ Hz (InGaAs-APD)
Reflectance (ρ)	0.2
Transmitting/ receiving optical efficiency ($\tau_t = \tau_r$)	0.6

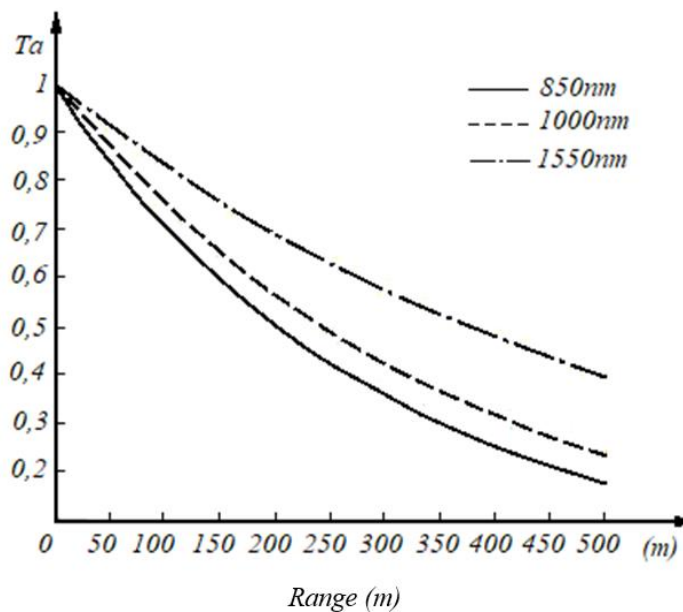


Figure 3. Squared attenuation factor (two-way).

Figure 3 shows the change of the two-way transmission coefficient T_a in the atmosphere versus range, corresponding to the laser wavelengths, with visibility $V < 6$ km. From figure 3 shows that 1550 nm laser has a stronger ability to propagate through the bad weather conditions than 1000 nm and 850 nm laser beams.

Figure 4 shows a graph of SNR versus range for laser systems as the visibility $1 \text{ km} < V < 6 \text{ km}$. With the probability ($P_d = 0.999$, $P_{fa} = 10^{-13}$) and FAR $10^{-4}/s$, the SNR value required to meet at least $\approx 11.88 \text{ dB}$ and all signals below this value are considered noise. According to the analysis results, as the FAR decreases, the SNR value required to meet the probability of detection 99.9% is observed to increase. It makes the maximum distance shorter to get the probability of detection 99.9%.

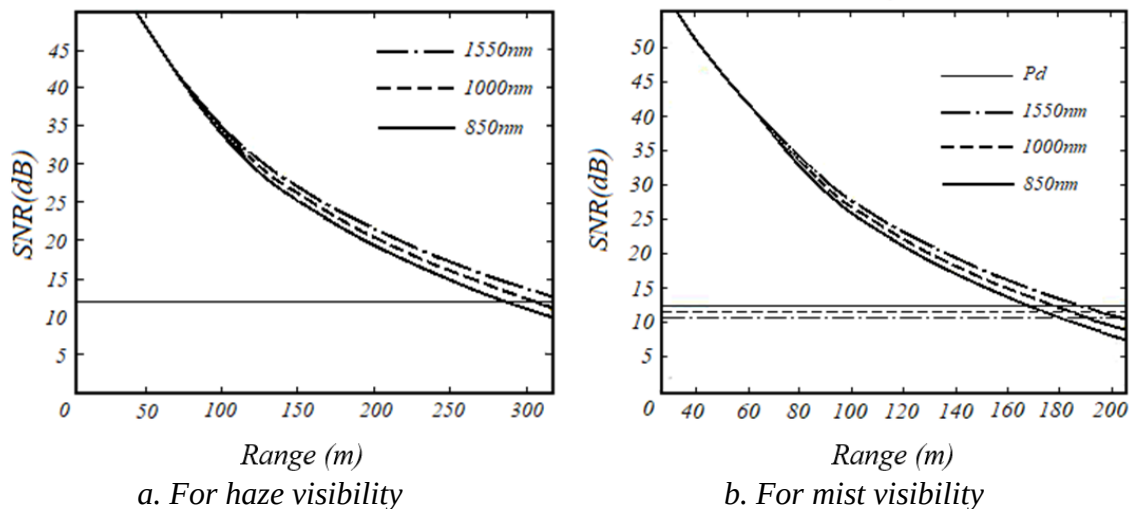


Figure 4. SNR versus Range (m).

Case 1. For haze visibility ($1 \text{ km} < V < 6 \text{ km}$)

From the fig 4a, the maximum detection range of 850 nm and 1000 nm laser system is about 150 m, while 200 m for 1550 nm laser system. The comparison results show that the detection capability of 1550 nm laser is stronger in poor weather conditions. So, development of 1550 nm laser system can improve performance in low visibility in haze conditions, and if advanced signal processing methods are adopted, the performance can be improved furthermore.

Case 2. For mist visibility ($0.5 \text{ km} < V < 1 \text{ km}$)

Figure 4b shows that the maximum detection distance of the laser system with wavelengths of 850 nm and 1000 nm is about 180 m; with 1550 nm wavelength laser, the largest detection distance is about 190 m. The comparison shows that the detection ability of the 1550 nm laser system is greater than in the mist condition.

Case 3. For fog visibility ($V < 0.5 \text{ km}$)

Figure 5 shows that the maximum detection distance of all three laser systems with wavelengths of 850 nm, 1000 nm and 1550 nm is about 160 m. In the conditions of a visibility greater than 2 km, using the 1550 nm wavelength provides the best target detection. However, in fog (visibility less than 500 m), the values for atmospheric attenuation are now the same between these 3 wavelength. In fog (and heavy snow),

there is no wavelength dependence; using the 1550 nm wavelength does not bring superior performance compared to the other two wavelengths in the condition that the distance of the fuze is less than 20 m.

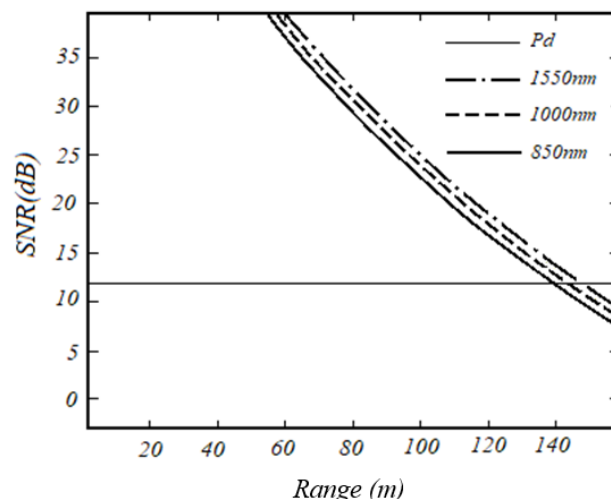


Figure 5. SNR versus Range (m) for the fog visibility.

4. CONCLUSIONS

In this paper, a model to evaluate the ability to detect target signals of laser fuzes in foggy and cloudy conditions is designed and implemented. The model is used to study the propagation of laser beams with wavelengths of 850 nm, 1000 nm and 1550 nm in bad weather conditions (limited visibility).

By comparing SNR and target detection probability between lasers using three wavelengths, the following conclusions can be drawn: (1) 850 nm and 1000 nm laser systems have good target detection in weather conditions with high visibility and much decrease in relatively bad weather conditions; The target detection distance is about 8% lower than the 1550 nm laser system. (2) Laser systems using the above three wavelengths have similar detection capabilities in fog conditions (visibility less than 500 m) when considering the effects of atmospheric attenuation.

This paper presents the results of evaluating the target detection efficiency of laser fuzes at different wavelengths in bad weather conditions that can be used as a basis when choosing the wavelength for laser systems in mid-range anti-aircraft missile fuze, and reference for the application of other laser weapon types.

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TÓM TẮT

ĐÁNH GIÁ KHẢ NĂNG PHÁT HIỆN MỤC TIÊU CỦA NGÒI NỔ LASER TRONG ĐIỀU KIỆN SƯƠNG MÙ

Bài báo đưa ra phương pháp đánh giá hiệu quả phát hiện mục tiêu của ngòi nổ laser hoạt động trong điều kiện có sương mù. Mô hình đánh giá được xây dựng từ: phương trình cự ly của hệ thống laser, suy giảm của chùm tia trong lan truyền hai chiều, các nhiễu tác động vào hệ thống; qua tính toán tỷ số "tín/tạp" đã xác định xác suất phát hiện của khối thu. Mô hình được sử dụng để đánh giá với bước sóng: 850 nm, 1000 nm và 1550 nm, khi lan truyền trong ba điều kiện sương mù khác nhau. Kết quả cho thấy, hiệu quả phát hiện mục tiêu của ngòi nổ tốt nhất khi sử dụng bước sóng 1550 nm trong tầm nhìn ở điều kiện sương mù mỏng (tầm nhìn $V > 500\text{ m}$). Trong điều kiện sương mù dày (tầm nhìn $V < 500\text{ m}$), ba bước sóng trên mang lại hiệu quả phát hiện như nhau. Bài báo cung cấp phương pháp và các chỉ dẫn lựa chọn bước sóng của ngòi nổ laser.

Từ khóa: Ngòi nổ laser; Bước sóng laser; Suy giảm chùm tia.

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