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Design and Construction of a Testing Platform and Estimating Attenuation Painting Reflectivity to Laser Beam

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Abstract:

The project has been described the design and construction of a reliable optical testing platform used for evaluate the reflectivity of metal surfaces treated with special paintings required for laser beam attenuation. The platform comprises an Nd-YAG laser system which has been designed and fabricated with specifications to be compatible with their corresponding in laser range finder transmitters used for various applications. The reflectivity of various attenuating paintings, at different detection angles, has been observed. Moreover, the variation of the reflected energy with painting type and metal type to be painted has been studied experimentally. Results illustrated the existence of a definite angle, at which the reflectivity was maximum (specular reflection). On the other hand, samples with attenuation paintings have constant very low diffusive reflectivity and are independent of the detection angle.

Key words: Nd-YAG laser, Attenuation, Paintings, Reflectivity of metal surfaces

Introduction:

The reflectivity, R, represents the ratio of the reflected beam power to the incident beam power. Since the output power may not totally reach the surface of the sample, therefore most of the published researches adopted a rational standard surface of extra high reflectivity at the studied wavelengths [1,2,3]. The surface is put at the site of the samples then its reflectivity is evaluated at the same measuring conditions of the samples. Due to the extremely high reflectivity of the standard sample, the amount of power that it reflects is considered to be equal to the incident power. In the current research, a polished gold surface has been nominated as the rational standard surface. This surface posses high reflectivity (approximately 96-98%) at the wavelengths of the laser used.

The reflectivity of the painted samples is compared to standard surface reflectivity and the percentage reflectivity can be computed employing the following formula [1, 2]:

$$R\% = \frac{R_{SAMPLE}}{R_{GOLD}} \times 100\% \ldots\ldots(1)$$

Theoretical Evaluation

Lambert’s law gives the relationship among the transmitted intensity, the incident intensity and the absorbing medium width. Mathematically, this law can be expressed by the following formula [4, 5]:

$$I = I_0 e^{-\alpha d} \ldots\ldots\ldots(2)$$

Where I is the transmitted radiation intensity, I_0 the incident radiation intensity, d represents the width of the absorbing medium and α is the absorption coefficient. This formula holds for monochromatic beam

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incident angle θ = 0 with respect to the normal to the surface of the pure non-dispersive medium.

Beer's law formulates the direct dependence of the transmitted radiation beam on the number of absorbing medium molecules as follows [4, 5]:

$$\log\frac{I}{I_o} = -\alpha Cd.......(3)$$

Where α is absorption coefficient per unit concentration and C is the absorbing medium concentration.

Reflectivity

Reflectivity R is defined as the ratio of the reflected beam power P_r from the surface of the medium to the incident beam power P_i. Thus, R is unitless with its value being limited from 0 to 1 and can be given by [6]:

$$P = \frac{P_r}{P_i}.........(4)$$

The study of reflectivity is one of the most complicated problems in spectroscopy [7]; it's not a definite feature of a sample like absorption and polarization. Thus, reflectivity is influenced by many parameters such as light intensity, illumination aperture, the composition of the sample surface and sample absorptivity. In addition, reflectance rays have different types. Mediums that capture 50% or more of the incident light energy are classified as absorbers, while others that reject more than 50% of the incident light are considered as reflectors. Gold, silver and aluminum are characterized by their extremely high reflectivity (reaching 95-98%) and, therefore, are considered specular reflectors. While carbon black, on the other hand, is a perfect absorber [4]. The reflector surface material plays a significant role in determining reflector type and the rate of the reflected light. Consequently, reflection can be classified according to surface material type: metals, insulators and semiconductors. Metals, usually, have high reflectivity due to their high electric conductivity. Fig. (1) demonstrates the reflectivity of some metals versus the incident light wavelength [7] .

Metals have non uniform reflectivity at shorter wavelengths and uniform reflectivity at the red and infrared regions [5] of the electromagnetic spectrum. Actually, metals are the best speculars. Insulators have relatively high refractive index (n >1), therefore they can be utilized as anti-reflection coatings.

At normal incidence of rays on a little bit rough surface, uniform reflection may not occur. By increasing the incident angle, the surface becomes less rough to light and uniform reflection increases. Thus, when light beam falls on a rough surface, the resulted reflection would be uniform (specular) only if the following condition is verified [8, 9]:

$$h\cos\theta << 1............(5)$$

Where h represents surface roughness height, θ is the incident angle.

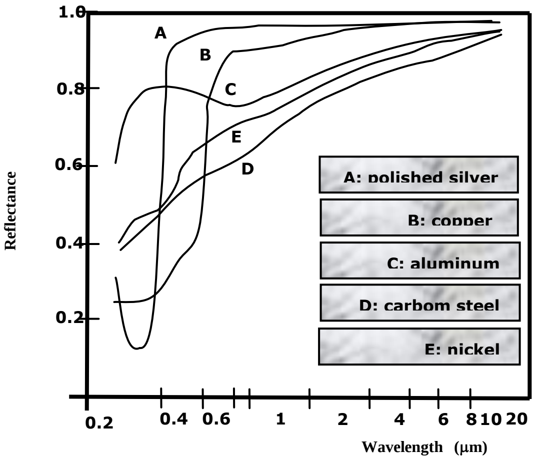

Fig. (1): The reflectivity of some metals versus the incident light wavelength [4].

Perfect (Specular) and Diffusive Reflections

The reflected ray resulted from the diffusive medium contains two apparent components:

The first one is due to uniform or specular reflection from the surface. For normal incidence, specular reflection Fresnel's equations are applicable and the specular reflectivity R is given by the formula [6]:

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \text{.........}(6)$$

Here n is the rated refractive index of the medium. In mirrors, k = 0

Moreover, k can be expressed by Lambert's law [4, 5]:

$$I = I_o \exp -\alpha d \text{.........}(7)$$

Where d is the transmission distance of the incident light beam (rays) inside the absorbing medium at which the intensity I_o decreases to I and α may be given mathematically by the formula [6]:

$$\alpha = \frac{4\pi\, k}{\lambda} \text{..............}(8)$$

Where α is absorption coefficient of the medium, k is a unitless constant which represents imaginary part of refractive index.

The second component of reflection occurs when the transmitted ray or beam undergoes multiple scattering from surfaces of particles composing the medium causing part of the beam getting back to the surface and appearing as a diffusive reflection.

The latter component involves valuable information about absorption because at least some parts of the diffusive rays penetrate sample particles through that short path in the direction of sample surface. Lambert's law relates the real attenuation and the penetration distance except for α is interpreted as a principal absorption coefficient of sample particles and becomes the thickness of penetration layer or, simply, the penetration depth.

Experimental Set-up

Fig. 2 illustrates the apparatus and instrument exploited in the project.

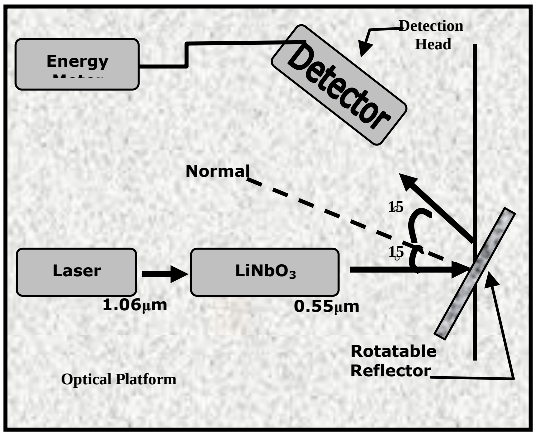

Fig. (2): Measuring and testing optical platform.

An Nd: YAG laser system has been constructed specifically for this platform. The specifications of the laser transmitter whose active medium is the Nd: YAG is:

- Laser wavelength = 1.06 μm
- Laser output energy = 15-30 mJ
- Beam divergence = 4 mrad.
- Pulse repetition frequency = 0.5 Hz

The block diagram of the power supply, charging and discharging electrical circuits that were constructed and used in driving the flash lamp required to the optical pumping of the Nd:YAG crystal is illustrated in fig.(3). By using frequency doubling non-linear effect the $LiNbO_3$ crystal exhibits, the output invisible wavelength 1.06 μm was transform to visible 0.55 μm. The latter visible beam was utilized as a guide beam accompanying the 1.06 μm wavelength in it's projection on the samples to be radiated.

A Melles Griot gold mirror was chosen as the perfect reflector. This mirror is mounted on a freely rotatable graduated base to facilitate visual observation and measuring of laser beam incident and reflected angles.

The energy of the laser beam reflected off the painted samples was determined via a pyroelectric thermal detector (Jenetic). The sensitivity of the detector is 2.9 V/J. The output signal of the detector was coupled to a Tectronics oscilloscope to register the reflected laser signal. The oscilloscope was capable of demonstrating more than one signal at a time. This is helpful in comparing the reference signal with signals reflected from the samples.

All the previously mentioned components were securely mounted on a Melles Griot optical alignment platform. Optical component alignment is crucial and vital to precisely deduce the incident and reflected laser beams.

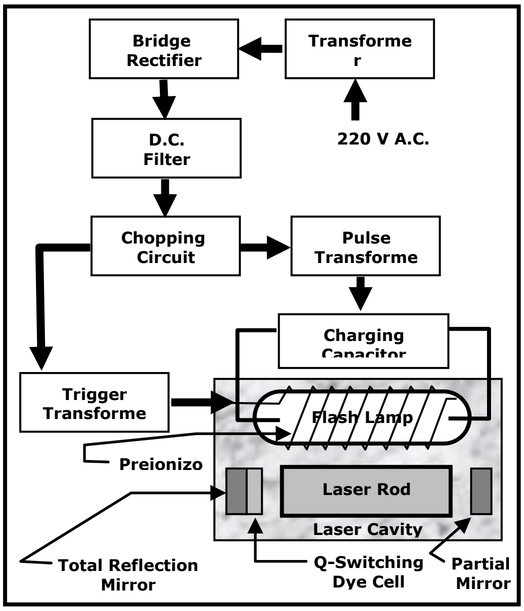

Fig. (3) Block diagram of the flash lamp power supply.

Measurements and Results:

This paragraph describes the method of measuring and calculating the reflectivity of both the perfect reflector (gold mirror) and the diffusive reflectivity (scattering of attenuating or camouflaging paintings). The resulted measurements are also summarized.

1. Measuring the reflected energy off the perfect reflector

Fig. 2 illustrates laser testing platform that has been fabricated to perform the measuring process of surface reflectivity. The incident angle of the laser beam 0.55 μm (and hence the 1.06 μm laser beam) is varied to get the perfect specular reflection of the laser and consequently the maximum received energy at the detector. The obtained results are outlined in table (1).

Table (1): Energy measurements with the incident angle.

Incident Angle θ	**Detector Received Energy mJ**
13	6.55
15	8.96
16	7.9
18	6.2

2. Calculating the diffusive reflectivity (scattering)

The diffusive reflectivity of the samples has been measured utilizing the previous method. The reflected energy from the perfect reflector (gold mirror) as received and measured by the detector was 26.2 mJ. The incident and reflected angles of laser beam were equal to 15°. Four stainless steel and aluminum samples were prepared to be painted (coated) and three other pressed polymeric samples were tested. The diffusive reflectivity of these samples was measured by applying formula no. (1). The results are briefed in table (2).

Table (2): Diffusion Reflectivity Measurements

Sample	Received Energy (mJ)	Diffusion Reflectance (Scattered) %
Stainless Steel 1	3.30	12.4
Stainless Steel 2-coated	0.96	3.60
Stainless Steel 3-coated	0.34	1.30
Aluminum 1	3.44	13.10
Aluminum 2-coated	0.34	1.30
Aluminum 3-coated	0.17	0.64
White Polymer 1	0.96	2.63
White Polymer 2	0.56	2.10
White Polymer 3	0.34	1.29

Conclusions:

The results of the laboratory testing platform in measuring sample reflectivity of camouflaging paints are extremely useful.

The best concealing paint can be easily selected from pre-tested data and transform it to a large scale that is applicable on field military vehicles and weaponries. This would reduce the efforts and costs of materials needed to be spent on developing the effectiveness of the chosen paints. It has been observed that the specular reflection of the gold reflector occurred at an incident angle of 15^o at which maximum detected energy of 8.96 mJ was recorded.

The incident and reflected angles of laser beams (the reference and the guided beams) can be smoothly altered since the platform is accommodated for optimum performance. This resulted in estimating the highest reflected energy from the various coatings, so one can experimentally study the relationship between the reflected energy and received detection angle. In addition to the Nd: YAG laser, CO_2 and GaAs lasers can be exploited on this platform by using the adequate detectors. The paints (coatings) used on the prepared samples that were tested via the optical platform have assured their effectiveness in attenuating and camouflaging the laser beam transmitted by the range finder as it was observed in the apparent reduction of reflectivity of these samples.

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تصميم وبناء منصة أختبار وتقييم أنعكاسية صبغات توهين أشعة الليزر

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الخلاصة:

يصف البحث تصميم وبناء منصة فحص بصرية معول عليها في تقييم ألانعكاسية للسطوح المطلية بصبغات خاصة مستخدمة لتوهين اشعة الليزر. تتضمن المنصة منظومة ليزر النيديميوم – ياگ المصممة خصيصاً بمواصفات متوافقة مع مثيلاتها المستخدمة في مرسلات مقدرات المدى الليزرية.
تمت ملاحظة الانعكاسية لصبغات توهين متنوعة وبزوايا كشف مختلفة. علاوة على ذلك، تم تجريبياً دراسة تغير الطاقة المنعكسة مع نوع الصبغة والمعدن المراد طلائه. أظهرت النتائج وجود زاوية محددة تكون عندها الانعكاسية أعظم مايمكن (أنعكاس مرآوي). من ناحية أخرى، العينات المطلية بصبغات التوهين تمتلك انعكاسية انتشارية متساوية، صغيرة جداً وبغض النظر عن زاوية الكشف.