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Implementation of output coupler mirrors for high damage threshold CO_2 laser: New technical approach

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Abstract

Multilayer dielectric mirrors are widely used in laser systems, especially when the laser requires optical elements for high damage threshold. New designed and manufactured procedures including the anti-reflective coating on a germanium sample at a wavelength of 10.6 µm using Physical Vapor Deposition (PVD) technique has been reported and developed. The applied parameters of the coating were at rotational speed of 10 rpm, under 2×10^{-6} mbar vacuum and at 150°C. As result of that, a good transmittance of about 96% was obtained, with a wavelength of 10.6 µm which was identified using Fourier transform infrared spectroscopy (FTIR). The output coupler designed mirror for CO_2 laser was manufactured using a polished germanium substrate. Multi-layer mirror coating was obtained consisting of the following materials (Zinc Sulfide, germanium, Yttrium oxide). The output result of these manufacture procedures was characterized with a reflectivity of 82%, which is the reflectivity required for this type of mirror, the implementation of manufactured mirror for CO_2 laser has been improved the basic laser energy capacity value which was changed from 250 mJ to 430 mJ. The laser used in these experiments for the manufactures mirrors was TEA CO_2 laser pulse, at 25 Hz frequency over long periods. The pulse energy has been measured using PM100D system which is equipped with measuring probe, type ES245C, The reported results have show perfect output coupler mirror for CO_2 laser and at an affordable cost comparing to mirrors made of ZnSe with no damage in spite of high laser power and long operation pulsing time.

1. Introduction

The successful development of high power CO_2 lasers especially for those being operated continuously at atmospheric pressure has created a demand for optical components capable of functioning without optical degradation at high power densities [1, 2]. Laser operation with long pulse causes damaging of optical components and is mainly due to thermal effects, arising from substrate absorption or optical coatings materials [3]. Although, the problem of light absorption by substrate materials at10.6 µm wavelength has received considerable attention [4, 5]. However, the published work on this subject, as well as the thin film absorption and its reduction are rather few. It has been found that the damage thresholds of dielectric thin films have not always correlated with the measured values of bulk absorption [6]. This is unexpected, since the optical properties of thin films generally differ from those of the bulk material due to differences in microstructure. It was therefore decided to investigate the absorption of thin films for a variety of materials regarded as being highly transparent at 10.6 µm wavelengths. Therefore, potentially suitable for using in coatings of optical components for high power laser applications. Due to the high transparency of these materials, a calorimetric technique was applied for absorption determination of both the uncoated substrate and the film/substrate combination by measuring the temperature rise when known power laser beam was transmitted. The absorption coefficient (imaginary part of the complex refractive index) of the film material was obtained from these two measured absorption values.

Semiconductors like germanium and zinc sulfide are widely used as optical components for the high power pulsed CO_2 laser systems due to their good physical properties, particularly at 10.6 µm wavelength (low absorption coefficient, good transmission in the infrared region). The main physical phenomena limiting the performances of 10.6 µm gas lasers are laser induced damage which affects both the transmission and reflection coefficients of the laser optical components. But, the main mechanism which is leading to the generation of laser induced damage in these semiconductor materials are not yet understood, which justifies intensive works on this subject. An important limiting factor at high power operation of lasers is the damage threshold of the optical components of the laser system [7].

The development of transversely excited atmospheric pressure (TEA) lasers has demanded the development of infrared optical components capable of withstanding peak powers above 10 MW/ cm^{-2}. High thermal conductivity for high-reflectivity gold-coated copper alloys are widely used for high-reflectance surfaces and single-crystal dielectrics, which was used as partially transmitting mirrors. Uncoated germanium is often used as the output coupling reflector due to its availability and low cost, as well as possessing a satisfactory dielectric reflectance of 78% at 10.6 µm.

In this paper, we have built and operated a TEA CO_2 laser, then, we observed the damage level in the uncoated germanium surfaces of the used output mirror. The laser was similar in design to that described by Lamberton and Pearson [8].

The first step in designing mirrors is the choice of materials as substrates and layers of optical coating to achieve the desired goals. These goals include designing mirrors with high reflection and high laser induced damage threshold. Selected materials should have high reflection and low absorption and since these mirrors are to be used in high power laser systems, the selected materials must have high laser induced damage threshold at the desirable wavelength. It is better to use materials that have high refractive index difference; because the greater the difference in refractive indices of alternating layers, the higher the reflection [14, 15]

One of the major objective of the reported work is to find out a method to manufacture locally with low cost multi-layers laser mirriro with high 1384fficiency for CO2 and TEA CO2 lasers In comparison with commercially available mirrores.

2. Experimental and discussion

2.1 Coated Sample Preparation

All samples (germanium Ge and Zinc Selenide ZnSe) were initially cleaned carefully, prior to any preparation procedures, using pure alcohol 99.99% as first stage. Subsequently, a mixture of diethyl ether and acetone solutions with a ratio of 70% and 30%, respectively were prepared to perform further cleaning using optical cleaning table and optical cleaning cloth. Finally, all samples were placed at suitable holders inside the physical vapor deposition system (PVD) chamber using evaporation tool (VTC 1000) at rotational speed of 10 rpm under vacuum 2×10^{-6} mbar and temperature of 150°C.

It should be materials and chemicals were purshed from Merck and used as received without any furthure purifications.

2.2 Coating materials calibration (deposition)

- *Zinc Sulfide, ZnS*

Zinc sulfide material can be applied as anti-reflection substance for germanium lenses at wavelength of 10.6 µm (germanium is used as a Parallel-Plate Lens). Optical thickness of a quarter wave-plate was obtained, equivalent to geometrical thickness of 1750 nm, at evaporation rate of 0.8 nm/sec using thermal resistance made from molybdenum (Mo) and applying thin protective layer of Y_2O_3 of 25 nm thick on both top and bottom of the ZnS layer at evaporation rate of 0.2 nm/sec using electron gun within the evaporation system (e-beam). Additionally, the oxygen gas has been introduced to the evaporation vacuum chamber at 3×10^{-4} mbar in order to complete the oxidation process inside deposition chamber. Spectroscopic measurements have confirmed the deposition of anti-reflection layer, where **Figure 1** shows the spectral line of a germanium sample before deposition process. It can be demonstrated that germanium transmittance in this case is about 46% at wavelength of 10.6 µm, while **Figure 2** shows the spectral line after deposition process. It can be shown that higher transmittance value of 65% was obtained at wavelength of 10.6 µm for ZnS coated material. Additionally, the other face of the germanium lens has been coated and the spectral line has demonstrated a huge transmittance of 96% at wavelength of 10.6 µm in the reported work, which is much higher than reported values in literature [9], in spite of the presence of protective layers of ZnS, as can be seen in **Figure 3**.

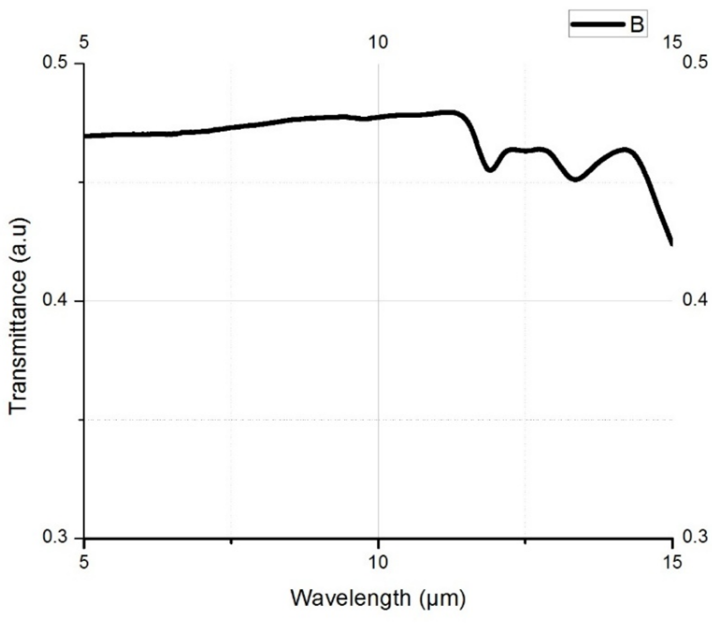

Figure 1. Transmittance versus wavelength for uncoated germanium sample

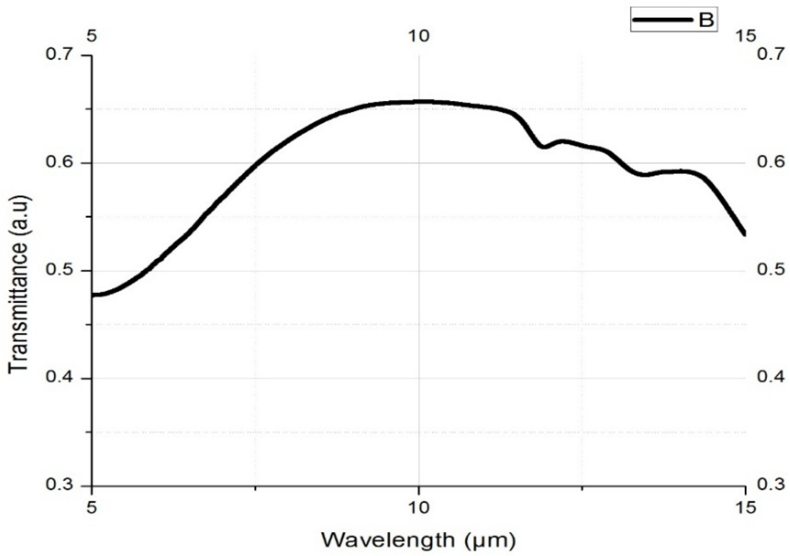

Figure 2. Transmittance versus wavelength for one side anti-reflecting coated germanium sample

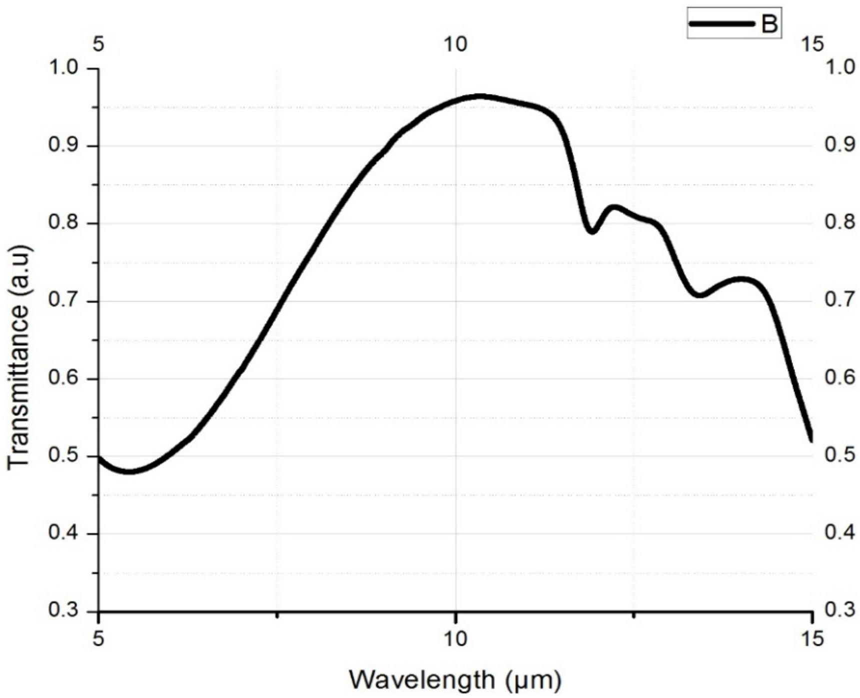

Figure 3. Transmittance versus wavelength for two side's anti-reflecting coated germanium sample

This material can be calibrated using ZnSe substrate (sample of Parallel-Plate Lens). The optical thickness of a quarter wave-plate was obtained, equivalent to geometrical thickness of 750 nm, at evaporation rate of 0.5 nm/sec using electron gun inside the evaporation system (e-beam). The spectrum demonstrates the required transmittance near the wavelength of 10.6 µm, where **Figure 4** shows transmittance of ZnSe before coating process, while **Figure 5** shows transmittance after coating an optical thickness of a half wavelength.

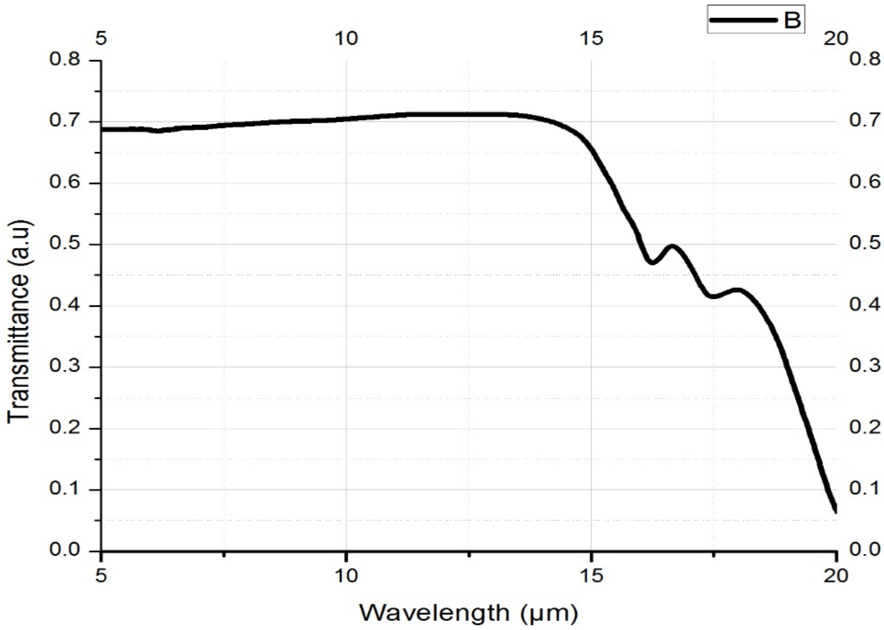

Figure 4. Transmittance versus wavelength for ZnSe without coating process

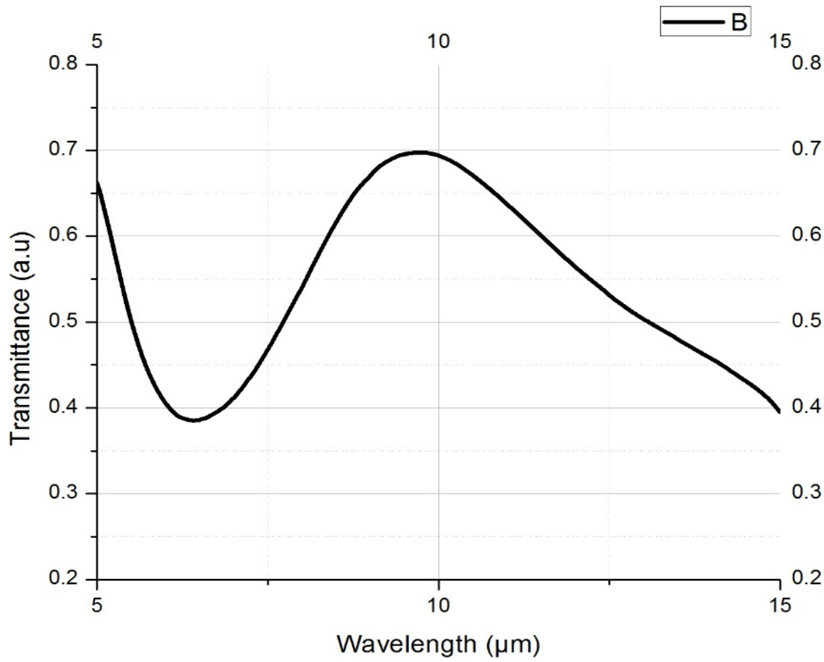

Figure 5. Transmittance versus wavelength for ZnSe coated by germanium with 1500 nm thickness

2.3 Deposition AR layer(s) on germanium

After determining the required thicknesses that forms anti-reflectance of germanium substrate, ZnS layer with good adhesion property which has been obtained by depositing Y_2O_3 nano layer, with thickness of 25 nm, on the germanium substrate, then depositing ZnS thin layer, and finally further Y_2O_3 nano layer, with thickness of 25 nm. These nano layers do not affect the spectral characteristics and enhance the physical qualities. They also have better resistance to both atmospheric effects and cleaning processes. However, ZnS layer must be calibrated in the presence of two oxide layers in spite of thin optical thickness of both layers. It has been noticed that applying matrix method to calculate spectral transmission [10] using the MATLAB program shows that the thickness of the ZnS layer should be reduced to about 0.2405 optical thickness, which is illustrated in **Figure 6.** A comparison was shown between the two graphs, which represent the theoretical transparency from the air into the germanium material for a layer of a quarter of a wavelength of ZnS and the theoretical transparency of the layers themselves with a difference that the layer of ZnS equals optically to 0.2405, while the displacement is clear when the layers correspond to a quarter of the wavelength of ZnS in the presence of Y_2O_3 layers with a smaller equivalent to 0.005 optical thickness.

2.4 Deposition of output laser mirror of CO_2 laser

Anti-reflective thin layer on the second face of the germanium mirror has been deposited with a transmittance of about 18%. This layer composes of anti-reflectance, germanium layer with geometrical thickness of about 750 nm and also a protective nano layer made of Yttrium Oxide of 25 nm thicknesses. **Figure 7** shows transmittance of the output mirror according to the previously mentioned design. We can notice a transmittance value of about 18% at the targeted wavelength, which corresponds to ideal output mirror. It can be suggested that the reported manufactured mirror can replace the ZnSe in CO_2 lasers which is consistence with the reported literature [13]. However, the ZnSe is costly and expensive, considered as highly toxic and its optical formation are rather complicated in comparison with the prepared mirror.

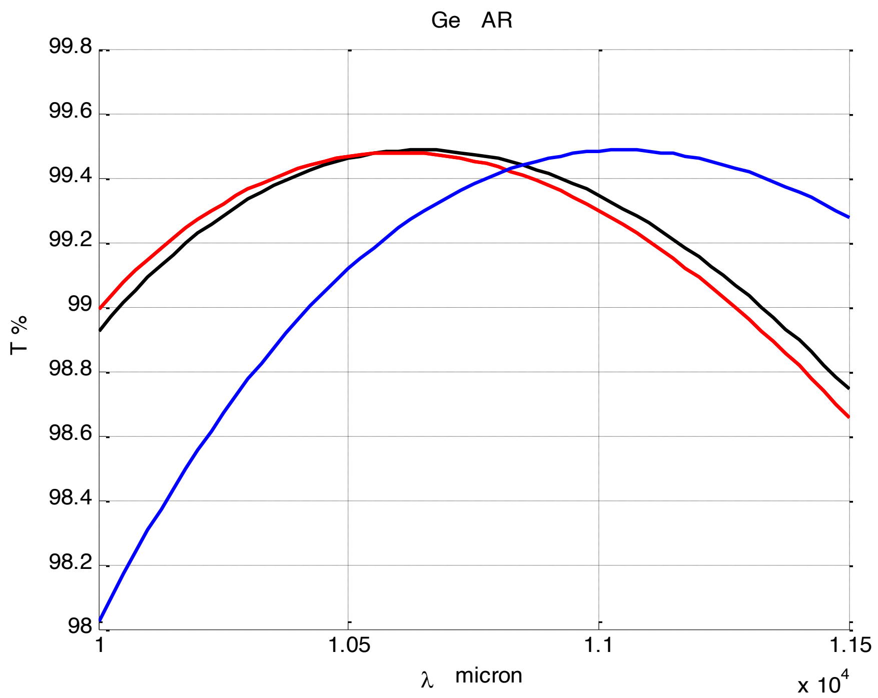

Figure 6. A comparison of the three coated layers. The red curve presents a quarter of wavelength of ZnS on germanium sample, the black curve represents the coating of 0.2405 optical thickness of ZnS wavelength with two layers of Y_2O_3 having 0.005 optical thickness, while the blue curve represents the coating of quarter of ZnS wavelength with two layers of Y_2O_3 having 0.005 optical thickness

2.5 Laser damaging Threshold

The laser applied in these experiments was TEA CO_2 laser with energy of 250 mJ and laser pulse frequency at 25 Hz. The effective medium dimensions are $1.5\times2\times30$ cm^3 and the input energy is 4 J. The laser resonator is hemispherical type (has a length of 57 cm) and the output coupler is uncoated germanium of Parallel Plate Lenses (its transmittance factor is about T_{OC}=46%), with 6 mm thick and 30 mm diameter. The rear total reflector mirror is concave and made of quartz coated by aluminum.

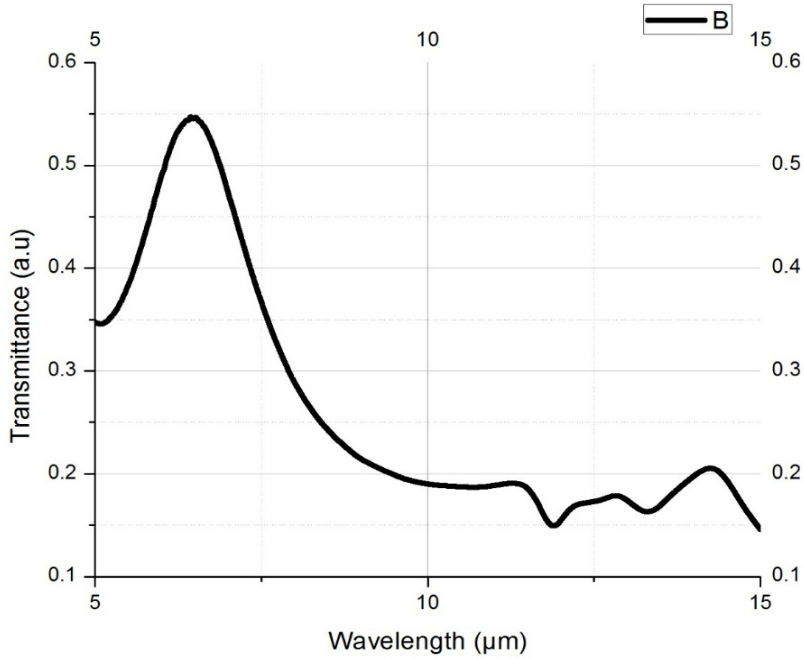

Figure 7. Transmittance versus wavelength for output mirror

An output mirror is similar to the one used in the laser cavity, but with major modification by introducing coated layer according to the previous mentioned design (i.e. transmittance factor of the mirror is T≈20%) [16-18]. The repeated experiments have demonstrated that the laser pulse energy has enhanced to 430 mJ levels, where pulse energy has been measured using PM100D system that is equipped with measuring probe, type ES245C [11]. **Figure 8** shows the shape of the laser spot on a thermal fax paper, where the laser spot dimensions is about 15×20 mm^2. In order to estimate the output pulsed laser peak power, the laser pulse width has to be measured. Photon Drag of response time that was not exceeding 1 ns which has been applied in this work. **Figure 9** shows the time changes of the output laser pulse, where it demonstrates that the pulse has two main components; the first is highly yield spiked pulse at short time (τ≈100 ns) and comprises about 30% of the pulse energy, while the second component of the pulse is a tail of low yield at long time (τ≈2μs).

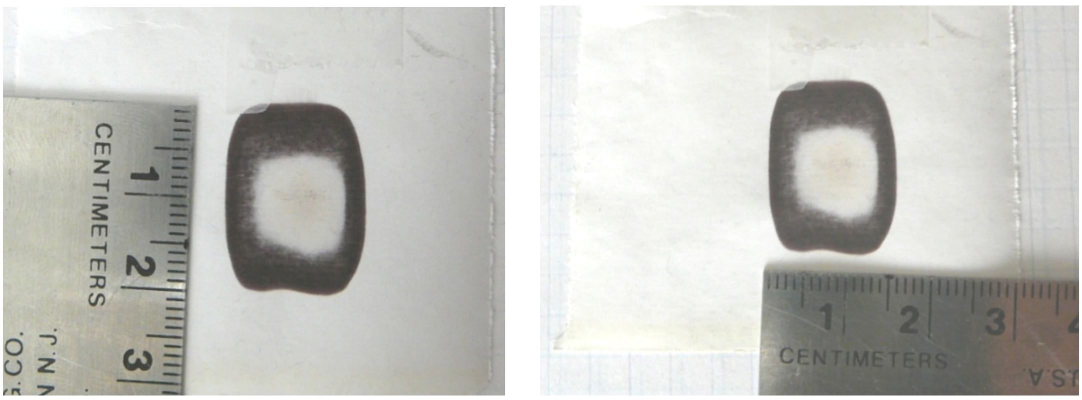

Figure 8. Laser Spot Trace on a Fax Paper

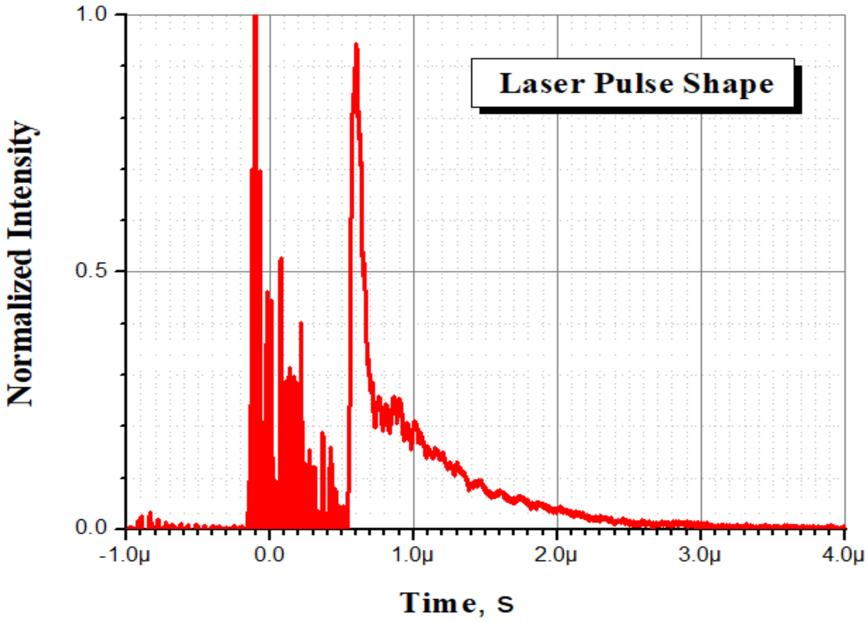

Figure 9. Laser Pulse Temporal Shape

Therefore, the power of the pulse is approximately equal to 1.44 MW. It is worth mentioning here that the damage threshold of germanium (as a substrate) is ranging between 0.6-11 MW/mm^2 at laser emission wavelength of λ=10.6 µm for pulse width of 100 ns [12].

Conclusion

Germanium mirror with transmittance of about T=20% was designed and manufactured. This mirror has been used as an output mirror in TEA CO_2 laser. The reported results have shown an improvement in laser performance due to the previous mentioned transmittance value, which is ideal for laser operation system (T_{opt}=15-20%). We have observed no damage for the prepared mirrors in spite of high laser power and long operation time pulsing.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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