Study on Monospectral Peak Identification of Hard Target Based on Brewster Angle

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Abstract. It is difficult to obtain the wide band spectrum of the target in the hard target detection with strong background weak signal by laser. A single spectral peak recognition method based on brewster angle is proposed. By combining the characteristics of polarized reflectivity and characteristics of typical target extinction coefficient, the brewster angle solution of hard target is obtained by extremum finding by the second derivative in the hard target detection model. The results show that the brewster angle of nonmetallic hard targets is correlated with inverse triangulation of double index. Therefore, the single spectral peak method can be used to identify the target material by means of the laser which covers the peak spectral segment of the target refractive index.

1. Introduction
In the field of weak signal detection under strong background noise, such as detection of dangerous road condition\textsuperscript{1}, determine internal quality attributes agricultural products\textsuperscript{2}, telemetry of dangerous goods at airport\textsuperscript{3}, space target detection\textsuperscript{4}, surface contamination detection\textsuperscript{5} etc., laser was used for its high-directivity, good monochrome performance, strong power and so on. There are several methods of hard target detection: 1)LIBS (Laser-induced breakdown spectroscopy)\textsuperscript{7,9}, and this technique excites the material to the plasma state by laser and obtains the information of the composition and concentration of the element by analyzing the position and intensity of the spectrum line of the light emitted by the plasma. LIBS is widely used in the analysis of elements, but rarely used in the analysis of organic compounds with the same molecular structure of elements. 2)Raman spectroscopy\textsuperscript{10,12}, and this technique stimulates inelastic Raman scattering and identify the target by analyzing Raman characteristic spectrum by laser irradiation. The disadvantage of Raman spectroscopy is its susceptibility to fluorescence interference. The latest trend of Raman spectroscopy is ultraviolet band Raman spectroscopy, that is, hard target is detected in ultraviolet band to avoid fluorescence interference, but there are not many substances with Raman characteristics in the ultraviolet band, so it is not widely used.
3) Absorption spectrum technology \cite{13,15}, and this technique identifies the target by detecting the characteristic absorption spectrum of the target. Typical technologies include TDLAS (Tunable Diode Laser Absorption Spectroscopy) and PAS (Photoacoustic Spectroscopy), etc. TDLAS detects target transmission by combining a narrow line width and high-power laser with a photoelectric detector. PAS detects target absorption based on photoacoustic absorption. After several years of development, the theory of absorption spectrum technology has been very mature, and a fairly complete spectrum library has been established. That's to say, absorption spectrum technology has a very wide range of applications. However, in the application of hard target detection, in order to identify the target material, absorption spectrum technology needs to obtain the target broadband spectrum by wide-band laser or multiple laser combination detection to accomplish the spectral identification. But too many lasers in detection system make the system bulky and costly. In order to solve this problem, a method of single-band spectrum hard target recognition based on featured Brewster angle is presented.

2. Hard target detection model

As Fig 1 shows, hard target detection model can be described in three layers\cite{5}. The first layer is radiation source, the temperature of radiation source is $T_1$, the equivalent blackbody radiance of radiation source is $B(T_1)$. The second layer is the surface of hard target, it can be regarded as contamination of hard target, the temperature of contamination is $T_2$, the equivalent blackbody radiance of contamination is $B(T_2)$, the reflectance of contamination is $R$. The third layer is the rest of hard target, it can be regarded as substrate. The temperature of substrate is $T_3$, the emittance of substrate is $1-R$. The equivalent blackbody radiance of it is $B(T_3)$. As the hard target in thermal equilibrium, $T_2 = T_3$. Then,

$$B(T_2) = B(T_3) \quad \text{(1)}$$

There are two radiation can be got by detector. The first radiation is the reflected light from source shown in blue arrow in Fig 1, the value of it is $B(T_1) \times R$. The second radiation is the substrate radiance shown in black arrow in Fig 1, the value of it is $B(T_2) \times (1-R)$.

$$L = B(T_2) \times (1-R) + B(T_1) \times R \quad \text{(2)}$$

Merge similar terms in equations (2).

$$L = (B(T_2) - B(T_2)) \times R + B(T_2) \quad \text{(3)}$$

![Fig 1 Hard target detection model](image)

Equation (3) is the expression of hard target detection model, from which it can be seen that: The difference of radiation source and substrate's equivalent black body radiation brightness exists in the product term of hard target's reflection features. Although the difference does not include hard target's reflection features, it will amplify the detection signals. The greater the difference is, the higher the detection sensitivity is, and the harder the target's features are easier to obtain. When the equivalent
radiation brightness of the external radiation source is much larger than the equivalent radiation brightness of the substrate, the influence of the substrate can be ignored, and the reflection characteristic information of hard target can be extracted directly from the signal.

3. Hard target detection model

Although the reflection feature of the hard target can be used to identify the hard target, in the practical application of hard target material identification, the reflection feature usually refers to the spectrum consisting of reflections from multiple bands of the hard target. It can be seen from the pPolarized reflection spectra in 800cm⁻¹-1300cm⁻¹ in Fig 2 that DMMP (dimethyl methylphosphonate) and PDMS (polydimethylsiloxane) have obvious spectral characteristics and can distinguish the two substances by spectrum. But the two spectra intersect in the black circle, where they have the same reflectivity. In the end, it is difficult to identify the hard target directly by the reflected signal when using the laser with narrow band.

According to Fresnel formula, the sPolarized reflectivity of hard target $R_s$ and pPolarized reflectivity of hard target $R_p$ are:

$$R_s = \frac{(n - \cos \theta_1)^2 + k^2}{(n + \cos \theta_1)^2 + k^2} \tag{4}$$

$$R_p = \frac{(n - \frac{1}{\cos \theta_1})^2 + k^2}{(n + \frac{1}{\cos \theta_1})^2 + k^2} \tag{5}$$

Where $n$ is refractive index of hard target, $k$ is extinction coefficient. From equations (4) and (5), it can be seen that the polarization reflectance is a complex expression related to the incident angle, extinction coefficient of hard target and refractive index, which takes great trouble to the process of target recognition. The refractive index and extinction coefficient are both parameters of hard target that reflect the characteristics of hard target materials. As shown in Fig 3, the extinction absorption coefficient spectrum have characteristic peak at 1024cm⁻¹, 1095cm⁻¹, 1261cm⁻¹, while the characteristic peaks of the refractive index spectrum are peak at 1009cm⁻¹ and peak at 1255cm⁻¹. The spectral features of the two are independent and in different shape. Therefore, the polarization reflectivity mixed with extinction coefficient and refractive index makes it difficult to identify hard target materials directly.

In fact, when the target is observed at different incident angles, the polarization reflectivity of the target will vary with the incident angle. According to equations (4)-(6), the relation between the polarization reflectivity of PDMS at 1000cm⁻¹ and the incidence angle can be calculated, as shown in Fig 4. And PDMS’ complex refractive index is shown in Fig 3.
Fig 3\cite{6} complex refractive index of PDMS

It can be seen from Fig 4 that the polarization reflectivity of p polarization decreases first and then increases with the increase of incidence angle, and there is an inflection point, which is the brewster angle of hard target in this band. When the hard target in the detection band is transparent, that is, the absorption coefficient is zero, the relationship between the brewster angle and the refractive index is shown in equation (6):

$$\tan (\theta_{\text{brewster}}) = n$$ \hspace{1cm} (6)

When the target is opaque, that is, the absorption coefficient is not zero, the mathematical expression of brewster angle ($\theta_{\text{brewster}}$) in the detection band of hard target is more complicated, which needs to be obtained by the method of calculating the extreme value of the second derivative. The second derivative of equation (14) can be obtained:

$$\frac{2}{\Psi} - \frac{2((n-x)^2+k^2)^2}{\Psi^2} + \frac{2(2n+2x)^2((n-x)^2+k^2)^2}{\Psi^2} - \frac{2(2n-2x)(2n+2x)}{\Psi^2}$$ \hspace{1cm} (7)

$x$ and $\Psi$ are listed in equations (8), (9).

$$x = \frac{1}{\cos \theta_1}$$ \hspace{1cm} (8)

$$\Psi = (n + x)^2 + k^2$$ \hspace{1cm} (9)
The inflection point of the function is the point where the second derivative is zero. By extracting the molecule from equation (7) and establishing the equation, we can get
\[
16k^2n^2 + 24k^2nx + 16n^4 + 24n^3x - 8nx^3 = 0
\] (10)
To simplify the solving process, the common factor of equation (10) is extracted:
\[
8n(2k^2n + 3k^2x + 2n^3 + 3n^2x - x^3) = 0
\] (11)
Since the refractive index \(n\) is not zero, equation (11) is equivalent to equation (12).
\[
2k^2n + 3k^2x + 2n^3 + 3n^2x - x^3 = 0
\] (12)
Solution to equation (12) is obtained
\[
\arccos \left( \frac{1}{2\sqrt{n^2 + k^2}} \right)
\]
Equation (13) is the mathematical expression of brewster angle in the laser detection of hard targets. It can be seen that the mathematical expression is relatively complex, which is a trigonometric function and a mixed mathematical expression related to refractive index and extinction coefficient, and it is still difficult to find out the law. Therefore, it is necessary to combine the physical meaning to further analyze.
In fact, in many occasions of hard target detection, such as road detection, agricultural products detection and explosives telemetry, the target surface is composed of non-metallic materials with tiny extinction coefficient (<1)\(^6\). Therefore, the square term of extinction coefficient \(k\) in equation (13) can be omitted and simplified to obtain.
\[
\arccos \left( \frac{1}{2n} \right)
\] (14)
Equation (14) is the mathematical expression of the hard target brewster angle of non-metallic opaque materials, from which it can be concluded that the brewster angle has nothing to do with extinction coefficient, but is related to the refractive index of the target. Therefore, “pure” spectral information can be obtained by detecting the brewster angle of the hard target, and the target material can be identified according to the spectrum.

4. Discussion
According to equation (5), the incidence angle corresponding to the minimum value of polarization reflectance of \(p\) polarization direction of each wave in 800cm\(^{-1}\)-1300cm\(^{-1}\) is taken as the brewster angle, as shown in Fig 5. For convenience of comparison, the brewster angle calculated by equation (14) based on the hard target detection model is also given in the figure. It can be seen from the figure that the spectral shape is very close, and the positions of the characteristic peaks of the 1000cm\(^{-1}\) band and the 1250cm\(^{-1}\) band are almost identical. The angle deviation in figure (b) in Fig 5 is due to the influence of \(k\) value in the model. The successful verification of the hard target detection model makes it possible to refer to the characteristic peak spectrum of refractive index in practical detection, select the laser covering the band, and obtain the brewster angle for detecting the band by angle scanning, so to realize the material identification of hard target.
5. Summary
A new method based on Brewster angle for material identification of hard target is proposed. It is found that the Brewster angle of nonmetallic opaque hard target is similar to the transparent target, and has nothing to do with extinction coefficient, but is related to the refractive index of the target. In the practical application of hard target laser detection, the target material can be detected and identified by the laser at the specific spectral peak based on the characteristic peak spectrum segment of refractive index.

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