Optical security verification by synthesizing thin films with unique polarimetric signatures

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This letter reports the production and optical polarimetric verification of codes based on thin-film technology for security applications. Because thin-film structures display distinctive polarization signatures, this data is used to authenticate the message encoded. Samples are analyzed using an imaging ellipsometer able to measure the 16 components of the Mueller matrix. As a result, the behavior of the thin-film under polarized light becomes completely characterized. This information is utilized to distinguish among true and false codes by means of correlation. Without the imaging optics the components of the Mueller matrix become noise-like distributions and, consequently, the message encoded is no longer available. Then, a set of Stokes vectors are generated numerically for any polarization state of the illuminating beam and thus, machine learning techniques can be used to perform classification. We show that successful authentication is possible using the k-nearest neighbors algorithm in thin-films codes that have been anisotropically phase-encoded with pseudo-random phase code.


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Nowadays, authentication of the information encoded in a physical support such as barcodes or quick response QR codes raises a real concern among potential users. The encoded information can be harmful since its origin cannot be validated easily. For instance, malicious codes can direct the browser to a harmful site without the user knowledge. Or tampered hardware with apparently legitimate codes may compromise an entire critical system. Recently, different methods have been proposed to help authenticate QR codes i.e. printing the code with special inks made with nanoparticles [1], use of random phase-only tags as an extra security layer [2] or to produce codes with metal nanoparticles [3]. In these cases, some physical properties of the code have to be measured in order to verify the origin of the message. In particular, the analysis of the state of polarization of the light that interacts with the code provides critical information that enables to classify the sample as trusted or non-trusted [3].

Thin film technology offers a huge number of possibilities for generating multilayer structures. Thus, the combination of different deposition technologies and treatments (physical and chemical vapor deposition, PVD and CVD respectively, thermal annealing, plasma surface treatments, etc), materials and compositions, number of layers and shuffling, layer thicknesses and combinations, homogeneous films and anisotropic films, internal structures of the films, surface structures, among others, provide great freedom of choice of parameters for many different and sophisticated optical effects [4]. The thin-film polarimetric encoded QR codes can offer unique characteristics: hidden parameters to the naked eye, immense difficulty to reproduce the QR item without a precise knowledge of all the deposition parameters, additional sensing parameters such as the wavelength and the angle of incidence needed for validation, fast image treatment algorithms to determine the authenticity or falsity of the QR logo, even in conditions of lack of information or disposition of a portion of the item. A final option offering this modified QR technology is the fabrication of singular and exclusive QR items, with no possibility of reproduction.

In this paper, we propose to use codes produced with thin-film technology for security applications. Thin-films structures illuminated with polarized light produce characteristic information that is used for recognition and identification purposes. Experimental measures are carried out by using an imaging polarimeter. This device enables the characterization of the components of the Mueller matrix of the thin-film. The use of this polarimetric method means a clear advantage when compared with previous studies since the knowledge of the Mueller matrix provides information about any possible polarization state. Validation of the code is carried out using image correlation or classification algorithms.

The paper is organized as follows: first, we explain how the thin-film samples are generated. Second, we introduce an effective technique that enables measuring the Mueller coefficients
of the code. In order to make more difficult the reproduction of the code, anisotropy is induced by placing pseudorandom phase masks such as small strips of scotch tape placed at random directions. Correlation is used to distinguish among true and false codes. Finally, the Mueller matrix is obtained in non-imaging conditions and thus its components become noise-like signals. This fact is used to perform authentication by means of machine learning techniques.

QR samples were fabricated by standard lithographic and deposition technologies on flat glass substrates (microscopy slides of 25 mm × 75 mm). The QR code used is shown in Fig. 1(a); the message encoded is a telephone number (0034934...). For the lithographic process we used AZ5214E photoresist deposited directly on a pre-cleaned glass by spin coating up to 6000 revolutions per minute during 30 s. The resulting thicknesses were typically of 100-200 nm, which provided satisfactory results after UV exposition (200 W Hg Arc lamp) during 47 s through the mask (see Fig. 1(b)). Finally, we carried out the development process using AZ400K developer (30÷120 in water) during around one minute. In order to have reproducible results, various trials were done to find the suitable parameters for the different steps (spin-coating parameters, cure time, exposition time, developer time, etc.) [4, 5].

Table 1. Deposition parameters of QR samples using RF magnetron sputtering from Cr and Ta targets.

<table>
<thead>
<tr>
<th>QR sample</th>
<th>Cr/glass</th>
<th>Ta2O5/glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developer time (s)</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Thickness (nm)</td>
<td>20</td>
<td>120</td>
</tr>
<tr>
<td>Target</td>
<td>Cr</td>
<td>Ta</td>
</tr>
<tr>
<td>Target-substrate distance (cm)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>Ar</td>
<td>Ar/O2</td>
</tr>
<tr>
<td>Flow ratio (sccm)</td>
<td>20</td>
<td>49/6</td>
</tr>
<tr>
<td>Pressure (Pa)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>RF power (W)</td>
<td>50</td>
<td>160</td>
</tr>
</tbody>
</table>

Fig. 1. (a) QR code. The message encoded is 0034934... (b) Negative and positive QR photography, based on a Kodalith-like film, to be used as a lithographic mask.

Fig. 2. Thin-films produced by RF magnetron sputtering through a QR photolithographic mask having a structure film/QR Mask/glass. Left: Ta2O5/QR/glass (120 nm thick). Right: Cr/QR/glass (20 nm thick).

Fig. 3. Diagram of the imaging Mueller matrix ellipsometer. PSG and PSA state, respectively, for polarization state generator and polarization state analyzer. The PSG and the PSA are composed of a polarizer (P) and a rotating compensator (C).
where $N = \cos(2\Psi)$, $C = \sin(2\Psi)\cos(\Delta)$ and $N = \sin(2\Psi)\sin(\Delta)$. The ellipsometric angles $\Psi$ and $\Delta$ are related to the complex Fresnel reflection coefficients for $p-$ and $s-$ polarized light ($r_{pp}$ and $r_{ss}$ respectively) by means of

$$\rho = \frac{r_{pp}}{r_{ss}} = \tan(\Psi) \exp(i\Delta).$$

Note that $\rho$ is a complex distribution that summarizes the polarimetric information of the measured samples. Figures 4(a) and 4(b) show the 16 Mueller matrix images measured for the Cr and Ta$_2$O$_5$ samples. Note that they follow the symmetry of Eq. (1).

From the information contained in the Mueller matrix images we calculate complex distributions $\rho_{Cr}$ and $\rho_{Ta_2O_5}$. We show that $\rho$ can be used for recognition purposes using phase-only correlation [8]. In 2007, Nomura used correlation to perform pattern recognition using holographic based polarimetric information [9]. Figures 5(a) and 5(b) display the auto-correlation for the Cr sample and the cross-correlation between Cr and Ta$_2$O$_5$ samples respectively. Results demonstrate that two identical QR codes produced with different homogeneous materials can be distinguished using correlation between parameters derived from a polarimetric analysis.

Because our polarization characterization method determines the complete Mueller matrix [6], the complexity of the QR codes could be enhanced by using layers and/or substrates of materials with optical anisotropy. When dealing with anisotropic samples, the number of polarimetric parameters intrinsic to the reflection process increases from 3 (the real and the imaginary part of the complex reflectance ratio plus the unpolarized reflectivity) to 7 independent parameters if depolarization is not considered [7]. For this reason we generated new samples by attaching pseudorandom phase masks using randomly oriented strips of scotch tape to the original thin-film structures. The corresponding Mueller matrix images are shown in Figs. 6(a) and 6(b). Interestingly, none of the 16 components of the Mueller-matrix images vanishes. In this case the calculation of the Fresnel coefficients becomes more complex because two extra Fresnel coefficients, $r_{ps}$ and $r_{sp}$, need to be considered. $r_{ps}$ and $r_{sp}$ describe the transformation of pure $p$-($s$-) polarized light to result in some $s$-($p$-) polarized upon reflection. Therefore ellipsometry measurements on anisotropic samples are usually reported using the three complex ratios $\rho = r_{pp}/r_{ss}$, $\rho_{ps} = r_{ps}/r_{ss}$ and $\rho_{sp} = r_{sp}/r_{ss}$. These coefficients for the Mueller matrices of Figs. 6(a) and 6(b) are calculated using the Cloude sum decomposition [7] which, by considering only the largest eigenvector of the decomposition, allows finding the closest Jones matrix corresponding to an experimental Mueller matrix. Then, phase-only correlation is used again to determine whether sample Cr is detected or not. Table 2 shows the normalized phase-only cross-correlation maxima for the Fresnel coefficients. Since the three values are very small, the Ta$_2$O$_5$ sample is rejected. For samples with scotch tape, phase-only correlation is again a good method to distinguish among the two classes.

Taking into account that the samples are phase-encoded, the Mueller components images become noise distributions if the
Table 2. Phase-only cross-correlations maxima for the samples with pseudorandom phase masks, that is, scotch tape. Values are normalized to the corresponding autocorrelation maximum.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$\rho_{\text{Cr} \otimes \text{Ta}_2\text{O}_5}$</td>
<td>0.040</td>
</tr>
<tr>
<td>$\rho_{\text{Ps} \otimes \text{Ta}_2\text{O}_5}$</td>
<td>0.020</td>
</tr>
<tr>
<td>$\rho_{\text{Sp} \otimes \text{Ta}_2\text{O}_5}$</td>
<td>0.014</td>
</tr>
</tbody>
</table>

camera objective is removed [2]. Even in this case, it is possible to distinguish between the two codes using machine learning algorithms. Note that the code can be validated or rejected without accessing the information encoded. Let $S = (I, Q, U, V)$ be the Stokes vector of an input beam. The polarization state of the beam after interacting with a sample described by the Mueller matrix $M$ is simply $S' = MS$. In order to generate enough information to perform successful classification, we calculate the Stokes vector $S'$ when the sample is illuminated with linearly polarized light. The polarization angle $\varphi$ ranges from 0° to 180° with a step size of 0.1°. This is equivalent to multiplying the experimental Mueller matrix images $M$ by the Stokes vector $S = (1, \cos(2\varphi), \sin(2\varphi), 0)$. The resulting Stokes vector ensemble $S' = MS = (I', Q', U', V')$ is composed of four groups of 1800 images. For classification purposes we take the 256-bin histograms of the 1800 images for each group $I'$, $Q'$, $U'$ and $V'$. The degree of polarization (DoP) is also calculated. Figure 7 shows some of the histograms of component $V'$ for the two thin-film codes for selected values of $\varphi$.

In summary, we demonstrated that codes produced using thin-films technology can be used in security applications. These codes produce a unique polarimetric signature. Characterization is carried out using a polarimeter able to measure the Mueller matrix of the samples. Codes are validated using correlation between polarimetric coefficients. Since the samples can be phase-encoded the polarimeter can also work in non-imaging conditions. In this way the polarimetric signals become noise distributions and the encoded information is no longer accessible. Nevertheless, codes can be still authenticated with the help of machine learning techniques. The proposed polarimetric optical thin-film security can be applied to a variety of optical security and encryption approaches [13–17].

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REFERENCES

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