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Design and fabrication of ultrathin lighting responsive security device based on moiré imaging phenomenon

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ABSTRACT

Security authentication of high- and low-value products is a pressing issue. Security technologies should be upgraded before they are counterfeited. In this study, an ultrathin lighting responsive moiré imaging device, which is different from traditional security device is developed for security authentication. Some interesting lighting responsive moiré imaging phenomena including light-activated three-dimensional floating imaging and light-controlled image transformation have been developed as covert security features for advanced authentication. These security features can be verified instantly using a point light source such as a white light-emitting diode configured in a smart phone. A compact defocus optical structure consisting of a micro lens-mirror array (MLMA) and a micro-pattern array is designed to fabricate the lighting responsive moiré imaging device. The structure makes the device ultrathin, which enables the easy integration of the device. The MLMA also overcame the difficulty in the fabrication of high numerical aperture micro-lens array required in traditional moiré imaging system. Flexible devices with 78-μm thickness were fabricated by photolithography, imprinting, and gravure-like techniques. Such thin device allows its potential integration with banknotes, currency, or other valuable documents/products.

1. Introduction

The counterfeiting or tampering of branded products is a serious problem for manufacturers, consumers, and government regulators. Investigations have indicated that counterfeited goods worldwide accounted for sales of more than $650 billion in one year [1]. These counterfeited goods refer to daily commodities, drugs, electronics, and so on. The range of goods subjected to infringement remains increasing. For security authentication, a great many anti-counterfeit technologies have been developed and updated. There are mainly two types of technologies for brand protection including covert and overt security feature techniques. Traditional covert security feature techniques using ultraviolet (UV) and/or infrared (IR) responsive inks, magnetic inks, machine-readable taggant-based inks, and DNA-based inks are generally detectable by trained persons using specialized and expensive devices [2–4]. However, in most cases, consumers need to verify the authenticity and safety of the products before they decide to buy or use them. Traditional overt security feature techniques include watermark, color shifting ink, pearlescent ink, hologram, and holographic device techniques. These techniques have been used for security authentication for decades [5–8]. The features can be readily understood by the consumers without specialized devices or foreknowledge. However, more and more commercial companies and even persons mastering these techniques can easily make or duplicate these overt features [9–11]. Thus, the security capability of these techniques has been discounted. Recently, artificial colors employing biomimetic and metallic nanostructures have been exploited to fabricate security devices [12–14]. These devices can provide high-resolution spectral or color images beyond the diffraction limit. However, it takes a long time for the consumers to distinguish the artificial color image from the holographic device. Moiré imaging phenomenon showing distinctive 3D and parallactic or orthoparallactic motion visual effects has also been used as overt security features [15,16]. Vivid periodic moiré images and aperiodic glass patterns have been designed and fabricated for security device. However, these images or patterns cannot respond to environmental stimuli, which limits the security capability and application of such devices.

Responsive optical devices that present switchable security features are attractive candidates for the advanced authentication of high-value documents or products. Such optical devices enable consumers to self-validate their purchases instantly [17,18]. Holographic devices are the typical responsive optical devices for security application [19,20]. These devices showing holographic image or color can display a different

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image or color upon detection of human breath or a drop of water [21]. It can also be combined with other overt or covert security features, such as hologram or UV responsive inks [22]. Holographic quick response (QR) codes by printable hologram technique enable the consumers to trace the source of the products by connecting the device to a database [20]. However, the response time of these devices mentioned above remains a bottleneck because of the limitation of the holographic material and/or the response mechanism.

Non-holographic lighting responsive imaging systems have been exploited in 3D display and material design domain. Reflectance field displays have been proposed for light responsive 3D display application [23,24]. Two layers of spatial light modulators have been used to fabricate passive light and viewpoint sensitive display [25]. Physical surfaces consisting of microfacets have been designed and optimized to get a custom surface reflectance material. Then, the desired surface appearance has been milled using a computer-controlled machine tool [26]. High-spatial resolution microstructures have been fabricated to get a bidirectional reflectance distribution function, which encodes the ratio of reflected radiance in each direction to the incident irradiance from each direction [27]. However, these lighting responsive imaging systems are not suitable for security application because of their bulky structures.

We have demonstrated a passive lighting responsive integral imaging system on a plastic film, characterized by the real-time interaction between the 3D image and the illumination environment [28]. These imaging systems are good candidates as optical security devices because of their intriguing performance. However, the reported light responsive integral imaging system is designed for a transmission-mode illumination environment. Thus, they can respond only to the transmitted light, which is different from the reflective illumination environment that we have been using in our daily life. In addition, to get a suitable view angle and compact structure, micro-lens array (MLA) with large numerical aperture (*N.A.*) is required for these systems, which enhance the fabrication difficulty of the imaging systems.

In this paper, an ultrathin reflective lighting responsive security device using moiré imaging phenomenon was designed and fabricated. The device could detect the reflective illumination condition and render a specific floating or motion image in real time. As the on/off state, the position and direction of the light source illuminated on the device varied, the transformed image could be formed immediately. Ultrathin lighting responsive moiré imaging devices were fabricated by integrating a micro lens-mirror array (MLMA) and a micro-pattern array (MPA) on a flexible polyethylene terephthalate (PET) film by photolithography, imprinting, and gravure-like technique. The thickness of the fabricated security device was about 78 μm. Light-activated floating images and light-controlled rotated, translated, and zoomed images were realized by changing the position and direction of the light-emitting diode (LED) relative to the security device. The LED is a point light source configured in a smart phone, which is popular worldwide.

Advantages of the lighting responsive security device include the following: (i) ultrathin reflective structure and real-time responsive ability, (ii) the security features can be detected and verified using a smart phone instantly and easily, (iii) vivid 3D imaging performance cannot be mimicked by other devices, and (iv) 3D images are immune to the chromatic uncertainty of hologram and holographic device.

2. Structure of the lighting responsive security device

The phenomenon of moiré imaging occurs when a micro-focus element array such as MLA is used to view a MPA with approximately the same pitch and the micro-patterns are situated at the focal plane of the micro-lenses. It is a type of moiré fringe in the form of a synthetic magnified image of the micro-pattern in the MPA. As shown in Fig. 1, the synthetic images were realized by progressive sampling and magnifying the micro-patterns with the micro-lenses. By carefully setting the pitch difference and the angle between the symmetry axis of the two

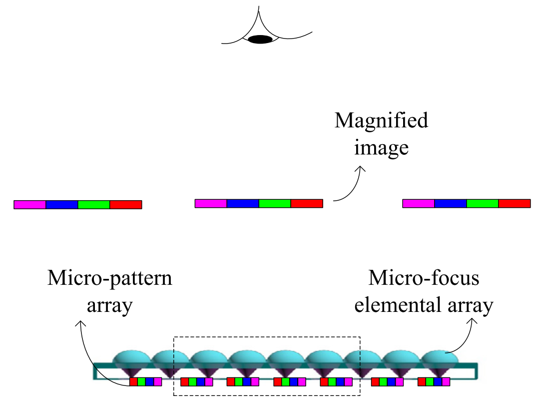

Fig. 1. Structure and imaging process of traditional moiré imaging system.

arrays, 3D floating and parallactic images or orthoparallactic motion images could be obtained. The thickness of the moiré imaging system was mainly determined by the focal length of the MLA. In security applications, a thinner device can be easily integrated. Therefore, a small aperture and a high *N.A.* MLA is usually used in traditional moiré imaging system.

The structure of the proposed lighting responsive moiré imaging device is similar to that of the traditional moiré imaging system, which is composed of a stack of micro-focus element arrays and MPA. Different from traditional moiré imaging system, a MLMA is used as the micro-focus element array, and the MPA is set out of the focal plane of the MLMA. The structures of the lighting responsive moiré imaging device and its light-activated imaging effects are shown in Fig. 2. The device consists of a MLA on the PET substrate, an MPA on the other side of the PET film, and a reflective layer coating on the bottom of the MPA layer. The MLMA is a combination of the MLA layer and the reflective layer, which functions as a micro-focus element array. These different configurations make the device respond to the illumination environment. When the device is lit up by a point light source, 3D floating images or motion images are formed around the film. When the point light source is turned off, the images disappear under the same bright ambient light. If we change the position of the point light source relative to the device, zoomed, translated, or rotated images will be formed.

3. Lighting responsive mechanism of the moiré imaging security device

Fig. 3 shows the imaging effect of the proposed security device under a diffused illumination. Each pixel in the MPA is out of the MLMA's focus and reflects a bunch of diffused light. This light is refracted by the lens and generates a diverged beam. These beams continue to transmit and overlap in the image space of the MLA. In the overlapping area of the beams, defocused images of the micro-pattern are formed. Indeed, in a daily diffused illumination environment, the diffused light will come from all the 4π solid angle. There will be many copies of the defocused images. These images overlap in the whole image space of the MLA and generate a diffused light field around the security device. Therefore, in such illumination condition, no resolvable image will be formed.

If a point light source is used to illuminate the device instead of a diffused illumination, there will be focused images around the device. If the symmetry axis of the MPA coincides with the symmetry axis of the MLA, the focused images are 3D floating images. If the MLA rotated with respect to the MPA by some angle θ, the focused images will be motion images with parallactic or orthoparallactic motion effects.

Fig. 4(a) shows the geometrical relationships among the point light source, device, and floating image, when the symmetry axis of the MPA