2018-8

Serialised holography for brand protection and authentication

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Recommended Citation

Vather, D. (2018). Serialised holography for brand protection and authentication *Applied Optics*, vol. 57, no. 22, pg. E131. doi.org/10.1364/AO.57.00E131

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Research Article | Vol. 57, No. 22 / 1 August 2018 / Applied Optics | E131

applied optics

Serialized holography for brand protection and authentication

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Received 29 March 2018; revised 28 May 2018; accepted 28 May 2018; posted 6 June 2018 (Doc. ID 327134); published 5 July 2018

The problems presented by counterfeit products and documentation are discussed. Limitations of existing holograms for anti-counterfeit applications are described. We describe the advantages of full holographic serialization and the requirements in terms of materials and techniques for mass production of true serialized holograms. These requirements having been met, we report for the first time the mass production of fully serialized holograms. The novelty of the approach consists of the direct use of the product manufacturer's information as the object in a holographic recording system along with a self-processing photopolymer and modular optical system to facilitate mass production of truly serialized volume holograms. Various types of serialized holograms for overt and covert authentication are described. We discuss briefly the application of Optrace's manufacturing methods for future generation holographic devices.

OCIS codes: (090.0090) Holography; (070.0070) Fourier optics and signal processing; (160.4670) Optical materials; (160.5335) Photosensitive materials; (230.6120) Spatial light modulators.

https://doi.org/10.1364/AO.57.00E131

1. INTRODUCTION

A. Extent and Implications of Counterfeit Goods and Documentation

The OECD has reported that counterfeit goods account for about 2.5% of global imports, with US, Italian, and French brands being hardest hit. The value of imported counterfeit goods was estimated at USD461 billion worldwide in 2013 and up to 5% of goods imported into the European Union are fakes from middle ranking or emerging economies, with China to the fore in such activity [1].

The effects are apparent in loss of revenue by reputable manufacturers and whole economies and danger to health, safety, and life itself. Counterfeit goods include pharmaceuticals that are substandard or contain substitute components inimical to health, dangerous toys, substandard medical equipment, machine parts, chemicals, and food, as well as luxury goods.

Counterfeit goods infringe trademarks, patents, and copyright.

Counterfeit activity also compromises personal identity, currency, credit and debit cards, and admission tickets and threatens confidence in the competencies of personnel at all levels in a wide range of professions through false academic qualification and certification [2].

The problem presented by counterfeit products has many aspects. First, fake products may be tolerated by original manufacturers, partly due to the perceived lack of cost-effective solutions or means of enforcement. Second, consumers can choose not to buy the genuine product simply because they cannot or do not wish to meet the cost. Third, the supply chain can be intercepted to substitute fake product for genuine, or to introduce genuine product manufactured in a lower cost economy.

2. ADDRESSING THE PROBLEM THROUGH OPTICAL SOLUTIONS

Solutions require active participation in the authentication process at various points in the supply chain and, at least in the case of on-line purchases, by the end user. The process should be rapid and easy to implement without the need for additional tools or equipment. Visual examination of an optical feature is one way to authenticate a product. A covert feature may be added requiring additional low-cost tools for authentication. At the highest level of authentication are devices which may only be interrogated by trained personnel using appropriate equipment and forensic types requiring spectroscopic and/or other rigorous laboratory analyses.

Currently available solutions include tamper evident labels, taggants having known spectroscopic signatures, radiofrequency identification, watermarks, optically variable devices including color changing inks, and holograms.

3. ANTI-COUNTERFEIT HOLOGRAMS

Holography has made a valuable contribution to product and document authentication, but it is becoming clear that the technology, as presently constituted, may be approaching the end of its useful life.

A. Hot Foil Stamped Holograms

Cost-effective mass production of holograms for authentication and brand protection purposes has long been based on the hologram recording method developed by Benton [3]. The technique introduced the crucial advantages that the holograms could be viewed in ordinary light, as opposed to laser light, and could be mass manufactured by hot stamping in metallic foil using a master, typically a surface relief hologram recorded in a photoresist and then electroplated with nickel metal.

Considerable effort has been made to produce foil holograms that display different optical effects when viewed from different angles or using different angles of illumination.

However, all the holograms made from a master are identical to one another and it is not difficult to make a replica of a surface hologram. Mass manufactured holograms, some made using rather crude replicas of masters, often escape notice through failure to subject them to even cursory scrutiny. There is a clear need to develop more reliable means of product verification and for those involved in the supply chain and end users to engage actively in the authentication process.

B. Volume Reflection Holograms

Volume reflection holograms based on the Denisyuk process [4,5] and recorded in silver halide, photopolymer, or dichromated gelatin, have made a valuable contribution to brand protection as they can also be viewed in ordinary white light. The use of counterpropagating object and reference beams during recording means that, for example, in a layer 30 μm thick there are typically 150 fringes of maximum brightness in the interference pattern and the recorded hologram acts also as a multilayer dielectric filter, selecting from the illuminating light during reconstruction the wavelength of the laser light used in the recording. Such holograms can be designed to present multiple images when viewed or illuminated at different angles. This is because the information stored in them is distributed throughout the depth of the recording layer so that more than one hologram may be multiplexed in the volume recording medium using different reference beams and objects for each one. Volume reflection holograms can be contact copied if only single beam geometry was used in recording the original.

4. HOLOGRAM SERIALIZATION

A. Current Practice in Hologram Serialization

Production volumes of foil stamped holograms may be up to 1 billion per year and their cost as low as €0.01 per hologram. Manufacturers can be reluctant to invest in anti-counterfeit innovations that add even minimally to overall cost so that even serialized holograms must be cost competitive. Serialization until now has meant that a product is uniquely identified by an inked or laser engraved alphanumerical text accompanying the hologram either alongside, underneath, or on top of it. The text itself has no holographic characteristics.

Surface ablation by single 6 ns laser pulses has been used to record holographic surface gratings in well-ordered, printed ink on a substrate, a process requiring a few minutes to complete [6] and which may also enable mass production of serialized holograms.

B. True Hologram Serialization

The goal of holographic authentication is to create volume holograms which are *holographically* serialized so that no two holograms are the same in appearance, nor share the same holographic data. All such holograms should facilitate easy verification by the end user by visual examination or using a machine reader. In this way hologram replication becomes pointless even if it were possible, as a copied hologram reported to a manufacturer's database would automatically be classed as a fake. While the cost per hologram may be more closely related to the value of the product that is to be authenticated, the level of protection is significantly improved, and revenue losses thereby reduced.

Optrace implements mass serialized hologram production by dispensing entirely with the use of a master hologram. All the alphanumerical data and images that are to be incorporated in a hologram are treated as the object (see Section 5.D) in a holographic recording setup. This object is illuminated by a laser to produce an object beam which is caused to interfere with a coherent reference beam. The resulting interference pattern is recorded throughout the depth of a photopolymer layer, creating a volume hologram. As in the laboratory, careful optical and optomechanical design are essential to ensure interferometric stability during the recording. Using this technique, it becomes possible to ensure that every hologram is completely unique and can be visually verified. The holographically stored information is retrieved using white-light illumination in transmission or reflection viewing.

5. MANUFACTURE OF TRUE SERIALIZED HOLOGRAMS

A. Photopolymer Recording Material

For cost-effective serialized hologram manufacture a photosensitive material should have the following characteristics:

(i) Requiring no physical or chemical processing after the holographic recording step. Chemical processing can significantly add to the complexity and cost of production and requires safe waste disposal in relation to the use of silver halide, dichromated gelatin, and some photopolymers.
(ii) High spatial resolution (several thousand cycles mm^{-1}).
(iii) Capable of being rapidly coated onto an appropriate support material.
(iv) Long pre-recording shelf life.
(v) Capable of recording a long-lived hologram without degradation or discoloration throughout its life cycle.

Optrace uses under license, one of the photopolymers developed and patented by the Center for Industrial and

Engineering Optics (IEO) at Dublin Institute of Technology. The Center specializes in research in photopolymers including acrylamide photopolymers and their applications, particularly in sensing and diffractive optics. The goal of IEO's early work on acrylamide photopolymer was to improve its spectral sensitivity and spatial resolution. Sensitization to green laser light at 514 nm was first reported by Martin *et al.* [7,8] and spatial resolution enabling reflection hologram recording by Meka *et al.* [9].

Liquid photopolymer consisting of monomers, a photosensitizing dye, a co-sensitizer, and a binder is coated onto a transparent substrate and dried.

In holographic recording photopolymerization takes place in bright regions of the interference pattern, consuming monomer molecules. The resulting spatial concentration gradient of monomer drives diffusion of monomer from dark to bright fringe regions where further polymerization takes place, increasing the refractive index modulation. The photopolymer's permeability must therefore be chosen to allow the diffusion of monomer molecules.

Detailed studies of the holographic characteristics of acrylamide photopolymer have been carried out by Martin *et al.* [10], Naydenova *et al.* [11], and Babeva *et al.* [12].

Hologram recording can involve spatial frequencies of several thousand cycles mm^{-1}. The response of the material at a point in space and time depends on what happens at other points [13]. Models describing the behavior of photopolymers, particularly at high spatial frequency, have been proposed. The nonlocal photopolymerization driven diffusion model [14] assumes that the polymer molecules grow away from their initiation point. Improved high spatial frequency response polymer may be obtained if this growth is restricted by chain transfer agents in the photopolymer composition. Increases in diffraction efficiency of a few percent have been obtained experimentally [15,16].

A two-way diffusion model [17,18] assumes that short polymer chains can diffuse away from the bright fringes, thus reducing the refractive index modulation especially at high spatial frequency. Thus, high laser intensity is to be avoided during recording as large numbers of photons delivered in a short time produce greater numbers of free radicals and greater numbers of shorter polymer chains and so the permeability of the matrix must also be adjusted to restrict diffusion of polymer molecules.

Further study and optimization of the photopolymer's physical properties has facilitated rapid coating at speeds of 18 $m.min^{-1}$ of liquid photopolymer onto low haze substrates in roll lengths of tens of kilometers to obtain dry, long-life, high-resolution holographic recording material with high optical quality, suited to step and repeat recording in a mass manufacturing process.

For industrial scale manufacture of serialized holograms, the photopolymer must have a long shelf life in liquid form. During a 45-week period samples of liquid photopolymer stored at a temperature of 3°C were deposited on glass substrates and allowed to dry overnight at room temperature. Holographic diffraction gratings of spatial frequency 1000 mm^{-1} were then recorded. The most important characteristic of such gratings is their diffraction efficiency (DE), the ratio of diffracted light intensity to the light intensity incident on the grating at the Bragg angle. The DE of the gratings was plotted against time in storage. From Fig. 1(a) it is seen that the DE remains constant irrespective of the time that the liquid photopolymer has been in storage.

Dry layers must also have a long pre-recording shelf life. Samples of dry photopolymer on glass substrates were stored for up to 60 weeks at both room temperature and at 7°C–8°C. The samples were heated to a temperature of 60°C for 1 h before recording holographic diffraction gratings of spatial frequency 1000 mm^{-1}. The results are plotted in Fig. 1(b) and again show that DE is not adversely affected by storage.

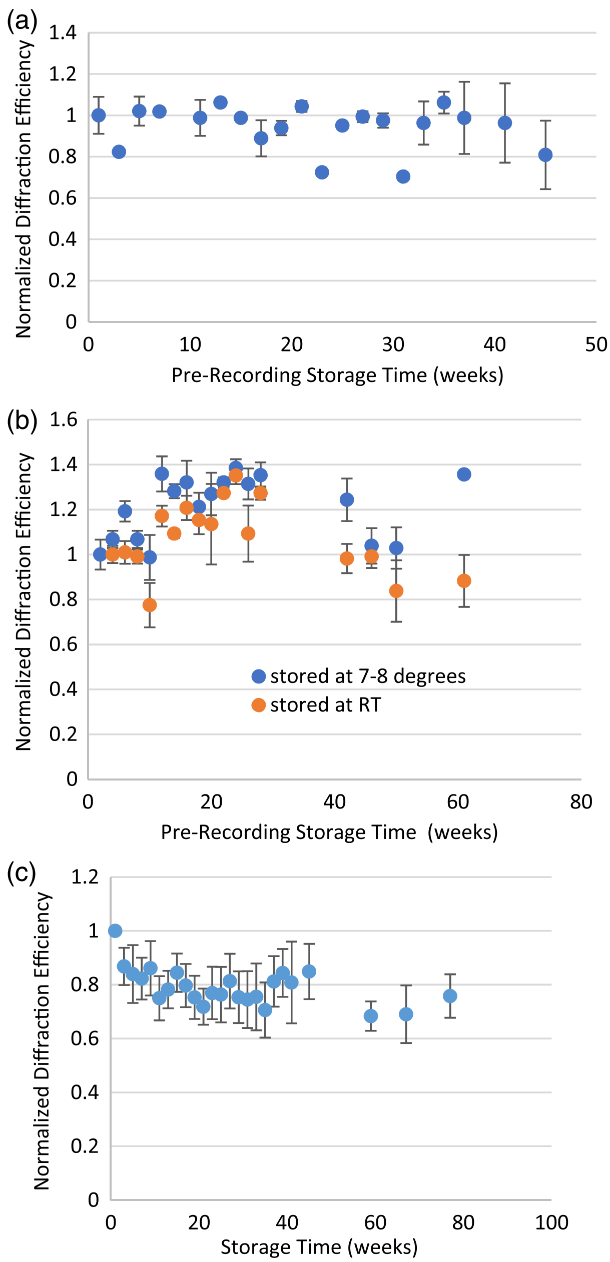

Fig. 1. Normalized diffraction efficiency versus storage time for (a) liquid photopolymer, (b) dry photopolymer layers, and (c) holographic diffraction gratings recorded in photopolymer.

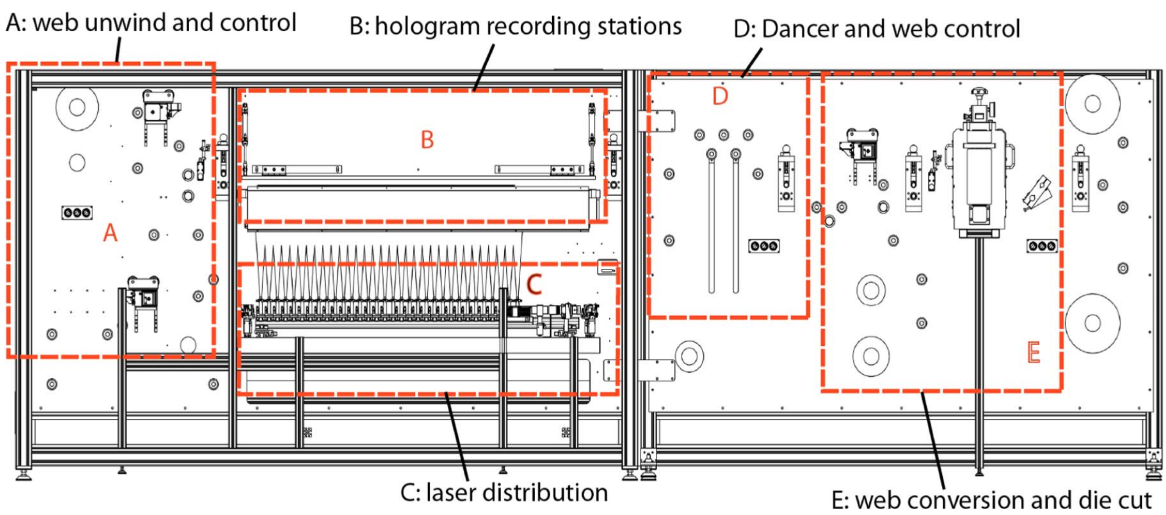

Fig. 2. Hologram production system. An unexposed roll of photopolymer is loaded onto an unwind roller in A. It then passes through a series of active tension control and guiding devices into B where it is clamped for recording. The laser beam distribution system C is described in the text. After recording the web is released and passes into the dancer section D where intermittent motion is converted into continuous motion. In web conversion section E an adhesive backing is applied, the web is die cut and waste matrix removed.

The recorded holograms must also be long lived. In Fig. 1(c) the diffraction efficiency of holographic diffraction gratings of spatial frequency 1000 mm^{-1} is plotted against time up to 70 weeks after recording and again no significant reduction in DE is observed. In this case the photopolymer was coated onto Melinex and a Melinex cover sheet placed on top.

B. Mass Production Systems

A production machine, shown schematically in Fig. 2, records up to 10,000 serialized holograms per hour. In the web unwind section A, the roll of dry photopolymer on a plastic transparent substrate is unwound and passes into the hologram recording section B.

The photosensitivity of many photopolymers is rather low, and this represents a bottleneck in the hologram manufacturing process. To overcome this difficulty a step and repeat process is implemented, enabling simultaneous recording of up to 100 different holograms in an equivalent number of recording stations laid out in two parallel rows in the hologram recording section, B. In section C a laser beam distribution system employing polarizing beam splitters and half-wave plates, splits a horizontally propagating, horizontally plane polarized, 532 nm laser into beams of equal optical power, each propagating vertically upward into one of the recording stations. Each station is equipped with standard optical components (beam splitter, lenses, plane mirrors) for the recording of off-axis holograms with the object data displayed on a spatial light modulator (SLM) (see Section 5.D). A constant tension accumulator, commonly called a dancer (section D in Fig. 2), facilitates compatibility of step and repeat hologram recording with the continuous roll-to-roll processes in the label conversion section (section E in Fig. 2) where the holograms are converted into labels. A reflective laminate is applied to the back of the photopolymer if required. A die cutter cuts out individual labels, unwanted matrix is removed from around the labels and a slitter splits the web in two. Rolls of completed labels are then wound up at the extreme right of the conversion section, E. Alternatively, in the application section (not shown), labels are applied to the user's web. Serial numbers and other data recorded in the holograms are verified by a machine vision system as matching the product manufacturer's data. Figure 3 shows a hologram production machine built at Optrace's plant in Dublin, Ireland, and installed at the user's plant overseas.

Figure 4 shows holograms emerging from the recording section, before conversion.

C. Point of Issue Hologram Production System

In certain applications, such as the preparation of secure documentation (birth certificates, passports, driving licenses, legal documents), serialized hologram production is required only on demand at different physical locations. The requirement for holograms is met by small point of issue production units, such as that shown in Fig. 5. A pre-prepared card having a designated area coated with photopolymer is inserted in a slot

Fig. 3. Left side, Optrace serialized hologram production machine 6 m × 1.75 m × 1.8 m. The user's web is at 90° on the right.

Fig. 4. Rolls of holograms emerging from the recording section and entering the conversion section. The two lower rollers in the group of five at left of center ascend and descend, ensuring compatibility of roll-to-roll manufacture with step and repeat holographic recording.

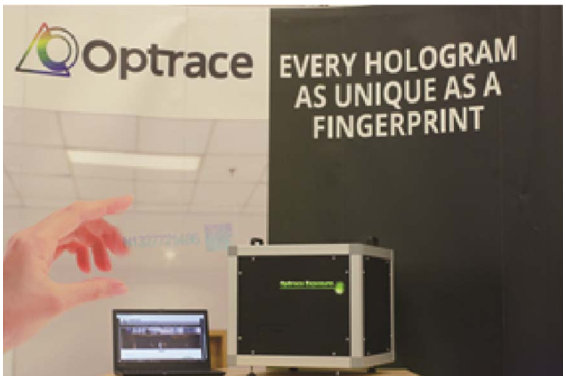

Fig. 5. Single holographic point of issue production unit. Dimensions approx. 50 cm × 50 cm × 40 cm.

in the unit for hologram recording and data is sent to the unit from a computer. The finished hologram may incorporate a quick response (QR) code and any other data required. A personal signature, provided on the spot by means of a touch-sensitive pad, may be included in the holographic recording.

D. Creating Object Beams

Images and alphanumerical data can be written to SLMs illuminated by laser light for holographic recording. Three different SLM types may be employed. One is a transmissive liquid crystal (LC) screen, essentially a pixelated LC panel sandwiched between transparent ITO electrodes. Each LC pixel rotates the plane of polarization of a plane polarized light beam traversing it, to an extent depending on the voltage applied to the pixel electrodes. Thus, spatial information encoded by the voltages applied to different pixels can spatially modulate the polarization plane of the laser. The spatial polarization modulation is converted to intensity modulation by a plane polarizer on the output side of the screen. Commercial LC screens have low transmissivity (~30%) and comparatively low resolution (few cycles mm^{-1}) although their cost is very modest. Higher-quality spatial light modulators are available but at much greater cost. Transmissive types providing both amplitude and phase modulation have largely been superseded by reflective liquid crystal on silicon phase only devices. One such device manufactured by Holoeye has an active area 15 mm × 9 mm with 10 megapixels, each 3.74 μm wide providing spatial resolution of 125 cycles mm^{-1} with 256 gray levels and a frame rate of 60 Hz [19].

Digital micromirror (DMM) technology offers a lower-cost solution with high reflection efficiency and spatial resolution. The plane of each micromirror is independently flipped from on (at +12° relative to the device plane) to off (at −12°) by the voltage applied to the underlying CMOS circuit. The active area is typically 15 mm × 8 mm consisting of about 2×10^6 micromirrors, each 7.56 μm in width, providing resolution of around 65 cycles mm^{-1} and frame rate up to 250 Hz with 8 bit gray level and 9.5 kHz with 1 bit binary [20]. Any required gray level is set by pulse width modulation of the driving voltage. Thus, for example, an individual micromirror driven by a rectangular wave form with a mark/space ratio of 20% will spend 20% of the recording time with its plane oriented at +12° to the plane of the device and 80% of the time at −12°. In practice a mark space/ratio of 100% is satisfactory for most recording purposes, that is, each micromirror is either in the on or the off position throughout the recording.

6. HOLOGRAM TYPES

A. Image Plane Transmission Holograms

The hologram may simply be an image-plane or near-image-plane transmission hologram, which, in white light, displays a serial number to be verified by reference to a serial number printed on the product package or by accessing the manufacturer's database. An example is shown in Fig. 6.

B. Holographic Quick Response Codes

Alternatively, a reflection hologram may take the form of a QR code that can be scanned by an Internet connected mobile telephone to obtain authentication from the manufacturer. Such codes exhibit classic holographic effects and are practically impossible to copy or transfer and so provide tamper evidence as well. Figure 7 shows an example.

It is important to emphasize that the QR code is a serialized volume hologram and represents an innovative solution that cannot be copied, providing strong protection against the use of fraudulent QR codes. Conventional QR codes are often

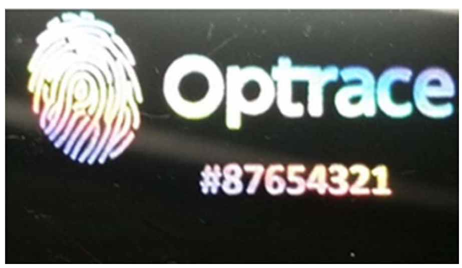

Fig. 6. Serialized image–plane transmission hologram, viewed in white light.

Fig. 7. Alphanumeric code (upper left) and the mobile telephone scannable QR code (lower right), are both holographic and unique to the reflection hologram (40 mm × 20 mm) shown. The other features, if required, may be repeated in many holograms.

secured using a hot foil hologram as an additional feature of the product label. Here, being a hologram, the QR code secures itself and furthermore cannot be photocopied. The unique data including product registration or serial number has been holographically recorded once only. Scanning the QR code is the first step in registration of the product and any subsequent attempt at registration is flagged to the manufacturer for appropriate action. Multiple scans producing the same product data may also be flagged as indicative of fraudulent code.

C. CODA

Covert optical devices for authentication (CODA), originally developed by IEO researchers, are Fourier transform transmission holograms recorded in photopolymer. In production machines the Fourier transform of an image is written to a DMM array and recorded as a phase image in a disk-shaped photopolymer layer inserted as a window 5 mm in diameter in a plastic identity card. When probed by a laser pointer, the image and its conjugate are displayed in the far field, as shown in Fig. 8.

For visual reading of the displayed CODA information a far-field distance of 1 m from the hologram to the display plane is normal. In machine reading applications a far-field distance of 200 mm may be used. Any human or machine visible wavelength may be used. Changing wavelength changes the separation between zero order and the displayed data. Furthermore, manipulation of the Fourier transform can increase the separation between the zero order and the displayed data for improved readability. The zero order may be removed by high-pass spatial filtering but the high diffraction efficiency of the Fourier hologram (up to 90%) results in acceptably low zero-order intensity for human or machine vision verification of the data.

CODA is normally intended for simple verification purposes but in certain applications requiring a higher level of protection against fraud, the data may be encrypted by spatial scrambling. An image processor equipped with the corresponding decryption key allows the reconstructed image data to be displayed.

For more advanced protection, double-random encryption [21] may be implemented. An image $f(x,y)$ is multiplied by a phase mask $\exp[j2\pi n(x,y)]$, where $n = RND[0,1]$. The result is convolved with an optical transfer function $h(x,y)$ whose Fourier transform is a constant amplitude, random phase function $\exp[j2\pi\nu(x,y)]$. The encrypted output having the appearance of white spatial noise, is

$$\psi(x,y) = f(x,y)\exp[j2\pi n(x,y)] \otimes h(x,y),$$

where $\otimes$ means convolution, and is holographically recorded. A unique phase mask can be used for each hologram. At reconstruction $\psi(x,y)$ is Fourier transformed and multiplied by the decryption key $\exp[-j2\pi\nu(x,y)]$. The result is Fourier transformed again to give output,

$$f(x,y)\exp[j2\pi n(x,y)],$$

and a CMOS or other imaging device will provide output $|f(x,y)|^2$. A similar double encryption system involves first converting the input $f(x,y)$ into a phase-only image $\exp[j\pi f(x,y)]$ providing significantly greater immunity to the effects of additive noise [22]. The encryption and decryption steps may also be implemented using computational methods.

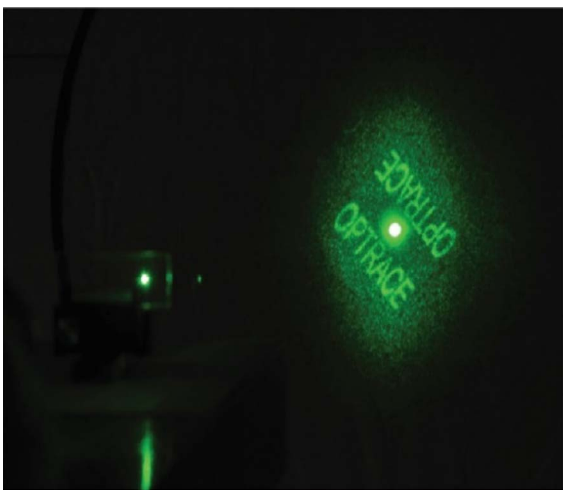

Fig. 8. CODA feature recorded as an image of its Fourier transform in the photopolymer layer left and displayed in the far field using a 532 nm laser pointer.

7. CONCLUSIONS

Optrace and IEO have successfully implemented mass manufacture of true serialized holograms for anti-counterfeit applications. These holograms can incorporate data such as serial number, lot number, coded location of original manufacture, and manufacturer's logo. Product data is converted into holographic form so that each hologram is as unique as the user wishes it to be. Similarly, holographic, serialized QR codes and Fourier holograms can be mass produced. We have described roll-to-roll manufacturing systems as well as point of issue machines. Manufacturing capability is based on spatial light modulators and self-processing recording materials having appropriate physical properties for use in large-scale hologram production.

Counterfeit activity is not going to cease any time soon, so the manufacturing techniques described are intended to be applicable to a wide range of optical device types and capable of meeting future challenges. For example, taggants can be added to the photopolymer for forensic-level authentication using spectroscopic methods.

Looking further ahead, interactive holograms that respond to changes in humidity [23], temperature [24], or pressure, or to the presence of specific analytes [25,26] will have a significant role to play in authentication applications.

Acknowledgment. I. N., S. M., E. M., D. Cody, and D. Connell: photopolymer development and aging studies. I. N. and M. Z.: CODA research and development. D. V., S. C., D. Connell, P. D., J. P., and S. McD: machine designs, construction, and commissioning. D. V., V. T.: optical system design, with assistance from Peter Collins. V. T. wrote the paper in collaboration with I. N., S. M., D. V., and D. Cody. All authors contributed to the development of serialized holography.

REFERENCES

1. Trade in Counterfeit and Pirated Goods: Mapping the Economic Impact, OECD, http://dx.doi.org/10.1787/9789264252653-en, April 2016.
2. http://www.bbc.com/news/uk-42579634, 24 January 2018.
3. S. A. Benton, "Hologram reconstructions with extended incoherent sources," J. Opt. Soc. Am. **59**, 1545–1546 (1969).
4. Y. N. Denisyuk, "Photographic reconstruction of the optical properties of an object in its own scattered radiation field," Sov. Phys. Dokl. **7**, 543 (1962).
5. Y. N. Denisyuk, "On the reproduction of the optical properties of an object by the wave field of its scattered radiation Pt. I," Opt. Spektrosk. **15**, 523–532 (1963).
6. F. D. C. Vasconcellos, A. K. Yetisen, Y. Montelongo, H. Butt, A. Grigore, C. A. B. Davidson, J. Blyth, M. J. Monteiro, T. D. Wilkinson, and C. R. Lowe, "Printable surface holograms via laser ablation," ACS Photon. **1**, 489–495 (2014).
7. S. Martin, P. Leclere, Y. Renotte, Y. Lion, and V. Toal, "Characterization of an acrylamide-based dry photopolymer holographic recording material," Opt. Eng. **33**, 3942–3946 (1994).
8. S. Martin, C. A. Feely, and V. Toal, "Holographic characteristics of an acrylamide-based recording material," Appl. Opt. **36**, 5757–5768 (1997).
9. C. Meka, R. Jallapuram, I. Naydenova, S. Martin, and V. Toal, "Development of a panchromatic acrylamide-based photopolymer for multicolour reflection holography," Appl. Opt. **49**, 1400–1405 (2010).
10. S. Martin, I. Naydenova, R. Jallapuram, R. Howard, and V. Toal, "Two-way diffusion model for the recording mechanism in a self-developing dry acrylamide photopolymer," Proc. SPIE **6252**, 625025 (2006).
11. I. Naydenova, S. Martin, R. Jallapuram, R. Howard, and V. Toal, "Investigations of the diffusion processes in self-processing acrylamide-based photopolymer system," Appl. Opt. **43**, 2900–2905 (2004).
12. T. Babeva, I. Naydenova, S. Martin, and V. Toal, "Method for characterization of diffusion properties of photopolymerisable systems," Opt. Express **16**, 8487–8497 (2008).
13. J. T. Sheridan and J. R. Lawrence, "Nonlocal-response diffusion model of holographic recording in photopolymer," J. Opt. Soc. Am. A **17**, 1108–1114 (2000).
14. J. T. Sheridan, M. Downey, and F. T. O'Neill, "Diffusion-based model of holographic grating formation in photopolymers: generalized non-local material response," J. Opt. A **3**, 477–488 (2001).
15. J. X. Guo, M. R. Gleeson, S. Liu, and J. T. Sheridan, "Non-local spatial frequency response of photopolymer materials containing chain transfer agents: I. Theoretical modeling," J. Opt. **13**, 095601 (2011).
16. E. Fernandez, R. Fuentes, M. Ortuno, A. Belendez, and I. Pascual, "Holographic grating stability: influence of 4, 4′-azobis (4-cyanopentanoic acid) on various spatial frequencies," Appl. Opt. **52**, 6322–6331 (2013).
17. T. Babeva, I. Naydenova, D. Mackey, S. Martin, and V. Toal, "Two-way diffusion model for short-exposure holographic grating formation in acrylamide-based photopolymer," J. Opt. Soc. Am. B **27**, 197–203 (2009).
18. D. Mackey, P. O'Reilly, and I. Naydenova, "Theoretical modelling of the effect of the rate of polymer chain immobilization on holographic recording in photopolymers," J. Opt. Soc. Am. A **33**, 920–929 (2016).
19. https://holoeye.com/spatial-light-modulators/gaea-4k-phase-only-spatial-light-modulator/ (2018).
20. http://www.ti.com/product/DLP6500FLQ (2014).
21. B. Javidi, G. Ahang, and J. Li, "Encrypted optical memory using double-random phase encoding," Appl. Opt. **36**, 1054–1058 (1997).
22. N. Towghi, B. Javidi, and Z. Luo, "Fully phase encrypted optical processor," J. Opt. Soc. Am. A **16**, 1915–1927 (1999).
23. I. Naydenova, R. Jallapuram, V. Toal, and S. Martin, "A visual indication of environmental humidity using a colour changing hologram recorded in a self-developing photopolymer," Appl. Phys. Lett. **92**, 031109 (2008).
24. T. Mikulchyck, S. Martin, and I. Naydenova, "N-isopropylacrylamide-based photopolymer for holographic recording of thermosensitive transmission and reflection gratings," Appl. Opt. **56**, 6348–6356 (2017).
25. D. Cody and I. Naydenova, "Theoretical modeling and design of photonic structures in zeolite nanocomposites for gas sensing. Part II: volume gratings," J. Opt. Soc. Am. A **35**, 12–19 (2018).
26. A. K. Yetisen, I. Naydenova, F. D. C. Vasconcellos, J. Blyth, and C. Lowe, "Holographic sensors: three-dimensional analyte-sensitive nanostructures and their applications," Chem. Rev. **114**, 10654–10696 (2014).