Surface-Plasmon Holography

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SUMMARY

Holography was originally invented for the purpose of magnifying electron microscopic images without spherical aberration and has been applied to photography for recording and reconstructing three-dimensional objects. Although it has been attracting scientists and ordinary people in the world, it is still a technology in science fiction movies. In this review, we discuss a new version of holography that uses surface plasmons on thin metal film. We discuss conventional holography and its drawbacks, such as overlapping of ghost and background due to the contribution of unnecessary diffraction and monochromacy for avoiding the unwanted diffraction components of different colors. Surface-plasmon holography is a version of near-field holography to overcome drawbacks of conventional holography. Comparison with conventional and volume holography for color reconstruction is discussed in reciprocal lattice space. Localized mode of surface plasmons and meta-surface holography are also reviewed, and feature perspectives and issues are discussed.

INTRODUCTION

Surface plasmon polaritons have been studied for many years in physics, electrical engineering, materials science, and even chemistry and biology. In 1899, Sommerfeld predicted the existence of surface light traveling along the metal wire (Sommerfeld, 1899). It was re-found and used as nano-waveguide light in the 1990s (Takahara et al., 1997). A bundle of metallic waveguides was used as a diffraction-free nano-lens in the 2000s (Ono et al., 2005; Kawata et al., 2008). Apart from this story, an optical scientist Robert Wood observed a plasmonic resonance phenomenon when he did an experiment of light diffraction at metallic grating in 1902 (Wood, 1902). The phenomenon was observed as a dark band in a rainbow spectrum. Such a dark band would not have been seen in the ordinary condition of grating alignment, except when the grating surface was accidentally wet with liquid. It was caused by the light absorption of high-order diffraction, due to the coupling of evanescent waves to the surface plasmons. This mechanism was explained much later (Fano, 1941). An optical geometry composed of a high-index prism and a metal plate with a small gap was proposed by Otto for the purpose of excitation of surface plasmons on metal surface (Otto, 1968). This geometry was modified to the one in which thin metal film was physically in contact with the prism to excite surface plasmons on the metal-film surface on the other side of prism (Kretschmann and Raether, 1968). This configuration has been applied to a bio-molecular sensor, named surface-plasmon resonance (SPR) sensor (Nylander et al., 1982; Matsubara et al., 1988a, 1988b), which has detected molecules or liquid due to the index change contact with the metal. In this article, we review the studies on the applications of surface plasmons to holographic display.

Besides the propagating mode of surface plasmons, the localized mode of surface plasmons has also been thoroughly studied. Such a mode has been known as the mechanism producing never-fading beautiful color of stained glass, which comes from metallic nanoparticles dispersed in glass (for example, Maier and Atwater, 2005). The spectroscopy of metallic nanoparticles in dielectrics was reported in 1904 by Maxwell-Garnett (1904). The resonance of localized mode plasmons found many applications, including the enhancement of Raman scattering at molecules (Fleischmann et al., 1974), super-resolving optical microscopy (Inouye and Kawata, 1994; Kawata et al., 2009), tip-enhanced Raman scattering microscopy (Inouye et al., 1999; Hayazawa et al., 2000; Stockle et al., 2000), nanoparticle lasers or SPASERS (Bergman and Stockman, 2003), cancer treatment (O’Neal et al., 2004), and photovoltaics (Ferry, 2008). The localized mode of surface plasmons has been also applied to holography, which we discuss in this review as well. We first discuss why and how surface plasmons have been applied to the holographic display. Holography was originally invented by Dennis Gabor as a lensless electron microscope, which did not suffer from the

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https://doi.org/10.1016/j.isci.2020.101879
spherical aberration caused by the electromagnetic lens that inherently limited the spatial resolution (Gabor, 1948, 1949). In addition, Gabor’s holography gains a magnification of, for example, 1,000 \( \times \), because reconstruction is made by light with wavelength 1,000 times longer than that of electron beam for recording. This work was awarded a Nobel Prize for “the invention and development of recording and reconstruction of three-dimensional light field” and attracted optical scientists and photographers. However, it still contains some problems for practical uses as a virtual display. A number of attempts have been made to solve the problems, such as separation of ghost images caused by unnecessary orders of diffraction (Leith and Upatnieks, 1964), elimination of the ghost caused by wrong colors for white-light illumination (Denisyuk, 1962; Benton, 1969, 1977), and near-field recording and reconstruction of hologram (Stetson, 1967; Nassenstein, 1968; Bryngdahl, 1969) for burying unwanted order of diffractions along the grating as near-field evanescent light.

**ELIMINATION OF GHOSTS AND BACKGROUND**

**In-Line and Off-Axis Holography**

In Gabor’s holography, the interference between the waves from a point source (black waves in Figure 1A) and the waves scattered at the object (red waves in Figure 1A) are recorded on a photographic plate. After the development of photographic plate (hologram), it is placed at the original location in the same optics without object. And then, the hologram is illuminated by a laser, to generate the waves of scattering at the object (red in Figure 1B) in the recording. As a result, the object is seen virtually at its original position (blue star in Figure 1B) by eyes. The conjugate component (black star) and 0th-order diffraction (diverging waves) overlap the reconstruction waves. Those unwanted diffraction components can be separated by dividing the illuminating beam into two with angle: one for illuminating the object and the other for directly illuminating the photographic film (Reference) as shown in Figure 1C (Leith and Upatnieks, 1964). The beam to illuminate the object is omitted in this figure for simplicity. Note that the waves of dashed blue lines in (B) and (D) are virtual.
\[ l = (r + o)(r + o)^* = |r|^2 + |o|^2 + r^*o + ro^* \]  
(Equation 1)

where * indicates complex conjugate. In the reconstruction, the hologram (assumed to be recorded in a positive film) is illuminated by reference beam \( r \), i.e.,

\[ rl = r(|r|^2 + |o|^2) + |r|^2o + r^*o^*. \]
(Equation 2)

If the intensity of reference beam is uniform in \( x \) and \( y \), this reduces to

\[ rl = r(1 + |o|^2) + o + r^*o^*. \]
(Equation 3)

Here, object \( o(x,y) \) is found as the second component of the right side of the equation, representing the reconstruction of the virtual object. The first component \( r(1 + |o|^2) \) represents propagating waves of reference (plane waves in black in Figure 1D), and the third component \( r^*o^* \) represents conjugate waves of \( o^* \) to image the object in the observation space in reconstruction. Due to the multiplication by \( r^2 \) this component does not overlap but separates from the object wave \( o \) in reconstruction (Figure 1D).

**Evanescent Wave Holography: Confined Light Waves on the Surface**

Although the ghost and background have been separated from the waves of the virtual object in off-axial holography, they still exist in the side where the eye or a camera is set, as shown in Figure 1D. These unwanted components can be removed from the observation by using near-field light or evanescent waves. Evanescent-wave holograms were developed by Nassenstein and Bryngdahl independently in 1968 (Nassenstein, 1968; Bryngdahl, 1969).

Figure 2A shows a typical configuration of evanescent-wave holography, where the reference beam is converted to the evanescent waves by total internal reflection at the surface of a high-index prism. The light
scattered at the object reaches the photographic film (or photo-resist) on the prism to interfere with the reference beam forming evanescent waves on the prism surface (not shown in the figure). The light illuminating the object and the reference beam originally come from the same light source but are divided into two. The object-scattered waves (marked in red) propagate through the prism and distort themselves due to the high index of the prism and the reflection at the prism edges. In addition, the object-scattered light reaching the photographic film reflects back due to the index difference between the free space (air) and the high-index prism as shown in Figure 2B. In reconstruction, the observer on the object side (free space) sees the object virtually in the prism side (Figure 2C).

Here, it is to be noted that the conjugate component is trapped in the hologram plane as evanescent waves. As a result, no ghost or background light deteriorates the holographic reconstruction. In addition, there is no light source or beam path in the observer side. The observer does not physically block the light path, which usually happens for the conventional reflection-type holography. The use of a planar waveguide or a light guide as a substitute of high-index prism makes this hologram system very compact (Lukosz and Wüthrich, 1976; Suhara et al., 1976).

**Surface-Plasmon Holography: Reconstruction from Opaque Film**

If a metallic film is coated on the prism surface under the hologram (photoresist) in the evanescent holography configuration (Figure 3A), surface plasmons can be localized on the thin hologram when the condition of SPR is satisfied by choosing incident angle and laser wavelength for illumination. Figures 3A and 3B show the configurations of recording and reconstruction for plasmon holography (Cowan, 1980). Silver and gold are typical plasmonic metals with a film thickness of 30–50 nm (Raether, 1988; Kawata, 2013).

In the recording system, the waves scattered at the object reflect at metal film and do not penetrate into the prism (Figure 3A), so that no stray light travels in the prism differently from the hologram. As a result, surface-plasmon holography is free from the ghost due to the stray light in recording (compare with Figure 2A). In surface-plasmon holography, the reflection of object waves at metal film is recorded as a hologram.
(Figure 3B). The observer standing in the object side (free space) sees the virtual object in the prism side in reconstruction (Figure 3C). When illumination light is off, the thin metal film works as a reflection mirror, whereas the virtual object appears behind the hologram when light is on.

The reference beam can also be given from the air side rather than from the prism side to record a hologram (Maruo et al., 1997). In this case, the size and the position of the virtual object in reconstruction differ from those of the original object. Figure 4 shows an example of reconstructed image set of surface-plasmon holography (Maruo et al., 1997). A planar waveguide and a light guide have been also used for surface-plasmon holography (Wang et al., 2001).

**COLOR REPRESENTATION**

**Raman-Nath Diffraction and Bragg Diffraction**

For reconstructing an object in color from a hologram, light with three colors (red, green, and blue) or white light is necessary. Figure 5A shows the reconstruction optics of Leith-Upatnieks’s hologram (a simple grating for the sake of simplicity) illuminated in three colors. Three color light reconstructs three virtual objects in different angles from the hologram, each in a different color. In Gabor’s holography, three objects are reconstructed at three different magnifications each in a different color. In both configurations, only one image in reconstruction is the true virtual object, whereas the other two are the false images to overlap the true one.

The generation of false images in wrong colors is explained in the reciprocal lattice space with use of Ewald sphere, which is known in crystallography. Figure 5B shows Ewald spheres (circles in the figure) for blue and red lights; light wavevectors $K_i$ and $K_d$ of incidence and diffraction, respectively; and the grating vector $K_g$. This hologram is assumed to be pre-recorded by blue light, so that in reconstruction blue-light with wavevectors $K_i$ for illuminating the hologram with grating vector $K_g$ generates diffraction $K_d$ on the Ewald sphere to form a closed triangle. For red light illumination, these three vectors do not form a closed triangle. Nevertheless, if the hologram is thin enough, the red light may diffract by the grating made in blue. Such diffraction is called as Raman-Nath diffraction. If the hologram is thin, the grating vector $K_g$ is not defined as a line in a given direction but the line end fans out in the reciprocal lattice space (a black line perpendicular to the arrow $K_g$ at the end in Figure 5B). As a result, false color images of the object emerge from a thin hologram.

If a hologram is thick enough (Figure 5C), only a selected wavelength of light (blue in Figure 5C) diffracts at the hologram, and light of other wavelengths transmit through the grating. Such a thick hologram was invented by Denisyuk (1962) and was called a volume hologram. Figure 5D shows the mechanism of volume holography in the reciprocal lattice space. Differently from Figure 5B, the grating vector $K_g$ of a thick grating does not fan, so that the diffraction of the wrong color (in red) by the grating $K_g$ recorded in blue does not couple with red light $K_d$ on the Ewald sphere in any angle. Such diffraction by the thick grating is called Bragg diffraction.

**Surface Plasmons for Color Holography**

Although Denisyuk’s volume holography has a great potential for practical applications, it has been limited in its applicability due to the durability and the lifetime of materials. On the contrary, thin holograms are durable, whereas not applicable to color representation with white light as discussed above, because they are Raman-Nath diffraction based. The authors have reported the use of surface plasmons for color holography with white light illumination (Ozaki et al., 2011). The mechanism originated from Wood’s finding of anomaly in grating diffraction (Wood, 1902) and SPR sensors for ultra-sensitive molecular sensing (Nylander et al., 1982; Matsubara et al., 1988a; 1988b).

Surface-plasmon holography has been explained already in the previous section from the viewpoint of the suppression of conjugate image and background. In this section, we discuss it as color holography. Even though surface-plasmon holography is classified in Raman-Nath-based thin-film holography, the false-color components disappear in reconstruction (Figure 5E). This can be explained with the dispersion relationship of surface plasmons (Figure 5F). The dispersion curve of surface plasmon asymptotically reaches SPR $\omega_{sp}$ of the metal in contact with the hologram. Light propagating in the air cannot couple with surface plasmons because the dispersion curve of light (a straight line in Figure 5F) does not cross or meet that of surface plasmons (a curve in Figure 5F). If the light is in a high-index prism, it reduces the speed (the angle of
light line becomes smaller in Figure 5F), and hence the light may couple with surface plasmons. The coupling occurs only at a selected color, for example, blue light at $\omega_{\text{blue}}$ in Figure 5F, the wavenumber $k_{\text{zBlue}}$ of which (more precisely, $z$ component of incident light $k_i$) is the same as that of surface plasmons $k_{\text{spBlue}}$, i.e., $K_{\text{zBlue}} = K_{\text{spBlue}}$. Other color light, for example, red light at $\omega_{\text{red}}$ does not couple with plasmons, or $K_{\text{zRed}} \neq K_{\text{spRed}}$. As a result, surface plasmons select a color from white light for reconstruction.

Figure 4. Example of Three-Dimensional Object Reconstruction from a Surface-Plasmon Hologram
(A) The reconstructed object is seen through the metal film on the prism in a distance. (B and C) Enlarged views at different view angles
Reprinted with permission from (Maruo et al., 1997). © The Optical Society.
More precisely, wavenumber \( k_{sp} \) of surface plasmons propagating on the metal surface is given by

\[
k_{sp} = \frac{\omega}{c} \sqrt{n_h^2 n_m(\omega)^2}
\]

(Equation 4)

where \( \omega \) and \( c \) are the angular frequency and the speed of light in vacuum, respectively, and \( n_h \) and \( n_m \) are the refractive indices of hologram media and metal, respectively (Raether, 1988). For simplicity, we discuss only the real part of refractive index, although \( n_m \) should be complex. \( n_m \) varies as a function of \( \omega \) as \( n_m(\omega) \).

For reconstructing a surface-plasmon hologram, the light is incident onto the metal film through the prism, and is converted to the evanescent waves to propagate along the metal film surface. The z component of wavenumber \( k_z \) of evanescent waves along the metal film is expressed as

\[
k_z = \frac{\omega}{c} n_g \sin \theta
\]

(Equation 5)

where \( n_g \) is the refractive index of prism and \( \theta \) is the incident angle.

The coupling between light (evanescent waves) and surface plasmons occurs only at the frequency at which z component of wavenumber is common to both. The configuration of surface-plasmon holography proposed by the authors is shown in Figure 6A, where a white light illuminates a hologram at three different angles (\( \theta \) and \( \phi \)). A virtual object is reconstructed in color (red, green and blue). As discussed above, due to the plasmon resonance at the selected wavelength, no ghost image with wrong color appears. To enhance the spectral separation in reconstruction, high-index material (\( \text{SiO}_2 \)) is coated on the hologram (the upper part of Figure 6B) to increase the effective index \( n_e \) in Equation (4) (Ozaki et al., 2013). The lower part of Figure 6B shows the enhancement effect of spectral separation. In the recording step, the
interference between object-scattered light and reference beam is exposed on photoresist film on the glass substrate to produce a surface-relief hologram, and then silver film is coated on the surface of the photoresist, resulting in a metallic plasmon hologram. SiO₂ film is then coated on the plasmon hologram by evaporation.

Figure 6C shows an experimental example of a three-dimensional reconstruction of an apple in color from a surface-plasmon hologram. A color object (in red, green, and blue) is observable in three dimensions by changing the viewing angle and viewing position (a movie in color is found in the article by Ozaki et al. (2011). A halogen lamp was used for reconstruction. Figure 6D shows an image of a bar taken by three-time exposure in R, G, and B to prove a good white-color balance.

Another version called a rainbow hologram, invented by Benton (1969), is also based on Raman-Nath diffraction, but does not suffer from the overlapping by unwanted color images for white-light reconstruction. Rainbow holograms have been successfully and widely used in credit cards as security codes. However, a rainbow hologram does not reconstruct a full (true) color object; a single-color image appears at a given viewing angle, and the color changes by rotating the hologram or by changing the viewing angle.

CATEGORIZATION OF NEAR-FIELD HOLOGRAPHY

Here we summarize different versions of near-field optical holography including surface-plasmon holography and evanescent holography, in terms of structures, mechanisms, and functions (Table 1). They are
categorized into non-plasmonic and plasmonic ones. Non-plasmonic holography based on total internal reflection with high-refractive-index material was reported in the 1960s (Stetson, 1967; Nassenstein, 1968; Bryngdahl, 1969) and with planar dielectric waveguides in the 1970s (Lukosz and Wü thrich, 1976; Suhara et al., 1976). In this type, holograms are placed in the near field of the prism or the planar waveguide, and ghost and background are not seen in the far field.

The surface-plasmon holography was first reported by Cowan in 1980 (Cowan, 1980), where a metal film is sandwiched between the hologram and a high-index prism (Figure 7A), so that it looks like a reflecting mirror when illumination light from the back is off (Maruo et al., 1997). The waveguide mode in the dielectric film coated on the metal can be used as reference light, where plasmonic resonance is not necessary for hologram recording or reconstruction (Wang et al., 2001).

Another configuration of surface-plasmon hologram is shown in Figure 7B, where metallic thin film and dielectric hologram are combined into one. The hologram is optically recorded on the photoresist film to form corrugation (height distribution) rather than density (index) distribution, and metal film is coated on it, following the surface corrugation of photoresist as a template. As a result, metallic film is corrugated

| Structures                        | Mechanism/Functions                                      | Authors/Inventors, Years |
|-----------------------------------|-----------------------------------------------------------|--------------------------|
| Non-plasmonic                     |                                                            |                          |
| High-index prism                  | • Total internal reflection                               | Stetson, 1967            |
|                                   | • Background/ghost free                                   | Nassenstein, 1968        |
|                                   |                                                            | Bryngdahl, 1969          |
| Planar dielectric waveguide       | • Waveguide mode                                          | Lukosz and Wü thrich, 1976 |
|                                   | • Background/ghost free                                   | Suhara et al., 1976      |
| Plasmonic                         |                                                            |                          |
| Metal film on high-index prism    | • Plasmon excitation with Kretschman’s configuration      | Cowan, 1980              |
| (Figure 7A)                       | • No stray light                                          | Maruo et al., 1997       |
|                                   | • Works as a mirror when no illumination                 |                          |
| Planar waveguide on metal film on | • Waveguide mode                                          | Wang et al., 2001        |
| prism                             | • Plasmon resonance is not necessary                      |                          |
| Metal film hologram               | • Uniform thickness of metal film                         | Ozaki et al., 2011       |
| (Figure 7B)                       | • SPP (surface plasmon polaritons) excitation is          |                          |
|                                   |   spatially uniformed                                      |                          |
|                                   | • The first report of plasmonic color hologram with       |                          |
|                                   |   white light illumination                                |                          |
| Metal grating (Figure 7C)         | • The first report on plasmonic hologram                  | Cowan, 1972              |
|                                   | • Unwanted diffractions appear and overlap the virtual    | Cowan, 1974              |
|                                   |   object image                                            |                          |

Table 1. Near Field Holography
as a metallic hologram (Ozaki et al., 2011). Blurring of an image due to the extended light source can also be suppressed with use of surface plasmons (Ozaki et al., 2012).

A higher order of diffraction of a grating can be also used for generating surface plasmons similarly to the Wood’s experiment discussed above (Wood, 1902). It was reported by Cowan in the 1970s (Cowan, 1972, 1974). In this configuration (Figure 7C), the hologram was photographic emulsion coated on the aluminum-coated diffraction grating. As this configuration contains two gratings (hologram itself and the grating to generate plasmons), unnecessary diffraction components by the coupling due to two gratings are generated, which contribute as ghost images to overlap with the reconstructed virtual image.

LOCALIZED PLASMONS AND METASURFACE HOLOGRAMS

Besides the surface-plasmon holography based on propagating surface plasmons, there have been reports on holography with use of localized-mode surface plasmons. Localized-mode surface plasmons are the standing waves of surface plasmons at a finite length of metal as Fabry-Perot interferometer of surface plasmons. As metal absorbs plasmons, Q factor of the resonance modes of this interferometer is low, so that the peaks of modes are broad, typically ~100 nm in wavelength spectrum (Sun and Xia, 2003). A variety of metallic nanoparticles have been proposed to excite localized modes. Among them, metallic V- or C-shaped nanostructures are of interest, because they work as sprit ring resonators to induce negative magnetic field in response to the electromagnetic (light) field at a given frequency. Electromagnetic induction in a three-dimensional array of nano-sprit ring resonators was reported for exhibiting extraordinary and exotic optical properties, such as negative refraction and cloaking, and was named as metamaterials (Smith et al., 2004). A two-dimensional version of metamaterials for hologram application was first reported by Shalaev’s group, as a metasurface hologram, where V-shaped nano-antennas were aligned to produce arbitrary phase distribution as desired on the substrate surface by optimizing the orientation and the angle of individual nano-antennas (Ni et al., 2013). Similarly to Fresnel lens, a light beam efficiently refracts by a metasurface hologram to produce a virtual image at some distance from the hologram.

Figure 8 shows an example of metasurface as a metallic V-shaped nano-unit array in line (shown in yellow at the top) and the refracting wavefronts as a function of distance from the array (Yu et al., 2011). Figure 9A shows a holographic reconstruction of 6 letters (8-μm wide for each), observed ~10 μm above the hologram with a microscope objective. A scanning electron microscopic image of a part of the hologram (letter P) is shown in Figure 9B; the lower right inset shows a magnified view of a part of V-shaped unit array (Ni et al., 2013).

Plasmonic nanostructures without the effect of electromagnetic induction have been also reported (Huang et al., 2013), where the phase of unit metallic nano-rod antenna varies as a function of antenna orientation with use of circular polarization. This was also called as metasurface holography (Huang et al., 2018).

Multi-color reconstruction is also possible with localized-mode surface plasmons with different sizes of nanoparticles. Figures 10A and 10B show the schematics and an experimental result of two-color holography (Montelongo et al., 2014). To suppress the unwanted localized mode that scatters the light in a wrong color, a well-designed two-dimensional rod/sphere arrangement of unit cells was proposed.
(Figure 10C). Or a hologram can be segmented into small blocks for different colors, each composed of rods of given length (Figure 10D) (Huang et al., 2015), which is equivalent to the painting of blocks in different colors.

The holograms with localized-mode plasmons, whether based on metasurface or non-metasurface, were not recorded optically, but they were fabricated one pixel by one pixel by e-beam (or focused ion beam) lithography, because localized-plasmon structures were too small to record with light. Those holograms were calculated by computer as solutions of inverse scattering problem. The spatial distribution of amplitude and phase at the hologram was calculated by the iterative back-propagation algorithm. The calculation result was printed with metal on the substrate by e-beam. This process took much longer than a real-time optical recording of hologram, and the size of reconstructed virtual object was often too small to be seen by the eyes. The optical recording with metallic nanoparticles has been reported with photo-reduction (Sugiyama et al., 2001; Kaneko et al., 2003), photo-migration (Vaia, 2001), and photo-ionization (Akella, 1997), although none of them have been applied to holography.

![Figure 8. Phase Propagation from Individual V-Shaped Nano-Antenna](image)
The upper images show the array of antennas (x-y) in yellow. A plane wave radiates out from the array (in x) toward z in the direction as designed. From (Yu et al., 2011). Reprinted with permission from AAAS.

![Figure 9. Experimental Result of Reconstruction from a Metasurface Hologram](image)
(A) Schematics of object reconstruction of metasurface hologram. The hologram and the reconstructed virtual object of six letters are both observed with a microscope objective.
(B) Hologram of letter P in (A) observed with a scanning electron microscope. The lower right inset shows a magnified view of a part of the V-shaped unit array. Scale bars, 5 μm (on top) and 500 nm (in inset), respectively. Reprinted by permission from Springer Nature (Ni et al., 2013).
CONCLUSIONS AND DISCUSSIONS

We reviewed the principles, the functions, the history, and the state of art of surface-plasmon holography and related topics. Surface plasmons add new functions to the conventional holography, such as ghost- and background-free imaging and color representation with white light illumination. Compared with volume holograms, surface-plasmon holograms are made of thin film, based on Raman-Nath diffraction. Surface-plasmon holography removes light sources from the observer’s space. Blurring due to the extended light source is also removed due to the narrow incident-angle resonance of surface plasmon. In the review, localized-mode surface plasmons and metasurfaces for the holography application were also reviewed. The principle and mechanism are fundamentally different from those of propagating-mode surface-plasmon holography in terms of recording process and color representation.

Holography has been competing with stereoscopy for three-dimensional viewing, which was invented in the 1830s (Wheatstone, 1838) and has been used for both personal and commercial use. It makes the viewers perceive scenes in three dimensions from two photographs pre-recorded with two cameras at different angles. Compared with the hologram reconstruction, the observers cannot change the viewing position and angle. Stereoscopy principle is now used in movie theaters as 3D cinemas. On the other hand, holography as a virtual movie appears only in the science-fiction movies, but has not been yet commercialized, except a few preliminary trials with a small number of frames as cinematographic holography (Leith et al., 1966; Bitetto, 1968; Yamaguchi et al., 1992). Recently, there was a report on cinematographic holography with metasurface holograms (Izumi et al., 2020).

The number of pixels is still insufficient to record and reconstruct a color movie hologram composed of phase and amplitude distribution in real time even with use of most advanced liquid-crystal spatial light modulators and CCDs. We have to wait for the arrival of further advanced electronics technologies.
ACKNOWLEDGMENTS

The authors started the surface-plasmon holography project when they were in Nanophotonics Laboratory at RIKEN, Japan. They would like to thank RIKEN for the generous support to pursue the project. The project has been done through fruitful discussion with our member Dr. Jun-ichi Kato, who passed away after the two authors left RIKEN. We would like to thank him and appreciate his contribution to this review article.

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