Surface plasmon polariton resonance and transmission enhancement of light through subwavelength slit arrays in metallic films

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Abstract: In this study, we present experimentally measured transmission enhancement of microwaves through periodic slit arrays in metallic films. Enhanced transmission peaks and sharp transmission dips are clearly observed around the theoretically expected surface plasmon polariton(SPP) resonance frequencies. Dependence of the transmittance spectra on the geometrical properties of slits is also demonstrated by varying the slit width, slit periodicity and the thickness of metallic films. Transmission peaks and dips are originated from the coupling between the incident light and SPPs which are caused by the slit array that acts like a grating coupler. The obtained results are theoretically explained by solving the Maxwell's equations and by the diffraction theory with appropriate boundary conditions, and they are in good agreement with those calculated by the finite-difference time-domain method.

OCIS codes: (240.6680) Surface plasmons; (240.0310) Thin films; (260.3910) Metal, optics of.

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1. Introduction

Since the extraordinarily enhanced optical transmission of light through subwavelength hole arrays in metallic films was experimentally reported by Ebbesen, *et al*. in 1998 [1,2], it generated large interest because it showed that much more light can be transmitted through hole array structures than Bethe's prediction reported in 1944 [3]. After the Ebbesen's work, many experiments have been performed to reveal the physical origin of the extraordinarily enhanced transmission [4–12]. It had been known that the origin of transmission enhancement through a grating structure is due to the resonant excitation of surface plasmon polaritons(SPPs) which can be described as the propagation of electromagnetic surface modes localized on metallic surfaces.

Since Hibbins *et al*. have demonstrated the coupling of microwave radiation to SPPs by reflection measurements [13], several experiments have been performed using a single hole or a slit surrounded by periodic grooves and these studies showed the existence of SPP modes on the periodically corrugated metallic surfaces [15–19].

SPP waves are non-radiative, therefore SPPs cannot be excited on met1allic films with freely propagating waves directly [29]. But implementing the periodic grooves or a hole array on metallic films as a grating coupling technique, the resonant excitation of SPPs is possible for specific wavelength. However, several studies have shown that the transmittance of the incident radiation is suppressed at the resonant wavelength and redshifted transmission peaks exist near the transmission dips [20]. These phenomena can be theoretically explained by scattering matrix by solving the Maxwell's equations with the surface impedance boundary conditions and diffraction theory [20].

Not only in optical and infrared frequencies, but also at microwave and terahertz frequencies similar studies have been performed using the scaling property of Maxwell's equstions [19,23–26]. In this study, we experimentally demonstrate the transmission enhancement of light through subwavelength slit arrays in microwave regime and compare the results with theoretical simulations. The transmission spectra are measured for various slit arrays to investigate the detailed dependence of transmittance on the geometrical parameters of a slit array such as the width of slit, periodicity of slit and metallic film thickness. The measured transmission peaks clearly show the enhanced transmission and the positions of transmission dips closely match the theoretically expected SPP resonance frequencies. Detailed discussion is addressed concerning the

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transmission properties related to the geometrical parameters from the comparison of the experimentally measured spectra with theoretically calculated results.

2. Experiment and Calculation details

In the experiment, we used several aluminum plates to demonstrate the transmission properties for various slit arrays. The size of plates are 450 × 450 mm^2 with the thickness of 4, 6 and 8 mm. Thin and long rectangular slits are periodically perforated on the aluminum plate to make a slit array structure. The length of each slit is approximately 350 mm so that it is large enough compared with the wavelength of incident light. The widths of slits are 3, 4 and 5 mm and the slit periodicities(center to center distance) are 15, 20, 25 and 30 mm. Transmission measurements are performed using a network analyzer(HP8722) and two rectangular microwave horn antennas, which are used as a source and a receiver, respectively, and each one is placed about 30 cm away from the sample as shown in Fig. 1. The two antennas are arranged to be in TM mode(magnetic field parallel to the slit) because of the property of surface plasmons. The horn sizes of antennas are 30 × 40 mm^2 and 40 × 50 mm^2 and antennas of each size covered two different frequency ranges: 10-18 and 18-26 GHz, respectively.

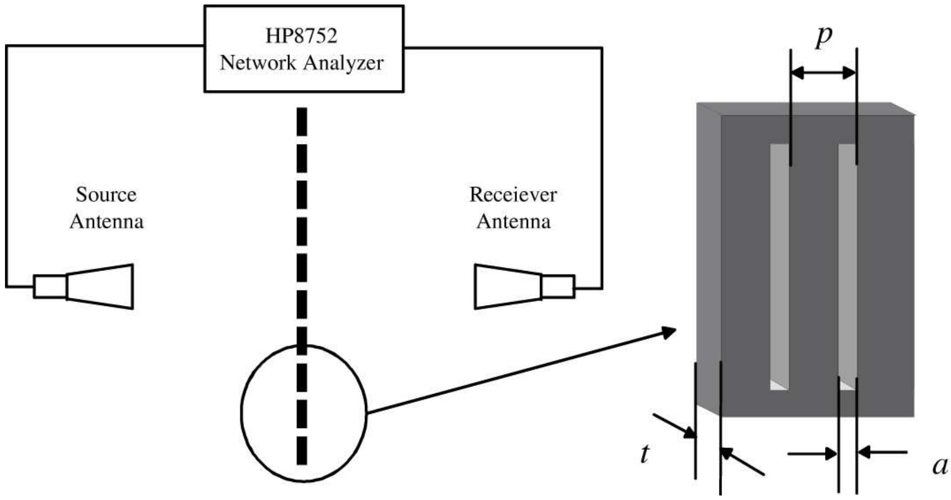

Fig. 1. Schematic diagram of transmission measurement setup. a is the slit width, p is the slit periodicity and t is the metallic film thickness

Theoretical calculations are performed using the two-dimensional finite-difference time-domain(FDTD) method [28] and also by the analytical calculations based on the Rayleigh's diffraction order expansion [20–22]. In the FDTD method, the permittivity of aluminum is modeled with the Drude dispersion model. But the permittivity of aluminum in microwave regime is a large negative, therefore, aluminum can be treated as an almost perfect electric conductor for the FDTD calculations at microwave frequencies. Though the aluminum is a perfect electric conductor, it had been known that SPP-like modes can exist on the surface of the metal with a periodic structure and these modes show almost the same behavior as the SPP modes. In this case, the periodic slit array excites the SPP modes on the surface of metallic films [14].

For the normal incidence of light, we can also get similar transmittance spectrum analytically using the zeroth order transmittance T_0 for an infinite array of periodic slits given by [23]

$$T_0 = \frac{2ia}{p\sin(kt)[1+k^2W^2]+2ikWp\cos(kt)}, \tag{1}$$

where

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$$W=\sum_{n=-\infty}^{\infty}\frac{\int_0^a \exp(i\frac{2\pi n}{p}x)dx\int_0^a \exp(-i\frac{2\pi n}{p}x)dx}{ap\sqrt{k^2-(\frac{2\pi n}{p})^2}},\tag{2}$$

Here, k is the wavenumber of incident wave, n an integer, a the slit width, p the slit periodicity and t the slit thickness. This equation was obtained by matching the cavity modes inside the slits with Rayleigh's diffraction order expansion outside the slits for the normal incidence case. The resonance dips in the transmission spectra can be explained by this equation because W diverges to infinity as k equals the momentum $2\pi n/p$ which is provided by the periodic structure.

3. Results and Discussion

First, we obtained the reference spectrum without the sample between the antennas. The two antennas are precisely aligned to face the center of the aluminum plates normally and the measured transmitted power of aluminum samples are normalized with the reference spectrum. The transmission measurements are made in the frequency range from 10 to 26 GHz, which corresponds to the wavelength of 11.6 $\sim$ 30 mm. Since the slit widths are set to 3, 4, and 5 mm, the subwavelength condition is satisfied over this frequency range.

From the dispersion relation of SPs and the momentum of light provided by the slit array, we can determine the SPP resonance wavelength of a given slit array for the normal incidence case to be [9]

$$\lambda_{\mathrm{SPP}}=\frac{p}{n}\sqrt{\frac{\varepsilon_m\varepsilon_{\mathrm{air}}}{\varepsilon_m+\varepsilon_{\mathrm{air}}}}\simeq\frac{p}{n},\tag{3}$$

where p is the periodicity of slit array, n an integer, and ε_m and $\varepsilon_{\mathrm{air}}$ denote the permittivity of metal and air, respectively. In the microwave regime, the permittivities of metals are very large compared with that of air, therefore we can simplify the above equation as p/n.

Figure 2(a) shows the normalized transmittance spectra of a single slit and a slit array for the slit width of 4 mm and the slit periodicity of 25 mm. The transmitted power through a single slit is very weak - only less than 1% of the input power is transmitted - while that of a slit array is much stronger. The maximum transmittance of the slit array shown around 10 - 11GHz is approximately 30% of the incident power which is much larger than the single slit transmittance considering the increased aperture area of multiple slits(15 slits on the metal plate). Even if we consider the reduced aperture for light by the opening ratio of a/p - which is 4/25 in this case, we can still argue that the maximum transmittance of 30% is extraordinarily enhanced value.

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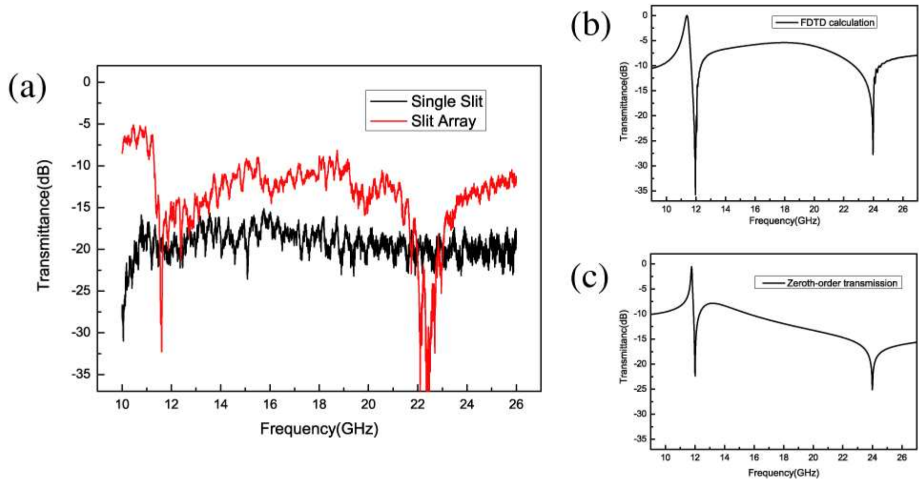

Fig. 2. (a) Measured transmittance of a single slit and a slit array. (b) FDTD calculated and (c) analytically calculated transmittance of a slit array when the slit width a is 4 mm, the slit periodicity p is 25 mm and the metallic film thickness t = 6 mm.

Transmittance spectra obtained by the FDTD calculations and also by solving Eq. (1) analytically are shown in Figs. 2(b) and 2(c), respectively. All the results in Fig. 2 show that a maximum transmission peak exists at lower frequencies than the first SPP resonance frequency 12 GHz expected in Eq. (3). Even though in the measured spectrum Fig. 2(a), this peak is not clearly shown due to the experimental condition, we can estimate that the maximum transmission peak would exist around 11 GHz as in the calculated results which show the transmission peak at 11.39 GHz in Fig. 2(b) and 11.77 GHz in Fig. 2(c), respectively. This difference between the measured maximum transmittance frequency and the expected SPP resonant frequency through a periodically corrugated subwavelength aperture has been reported in previous studies and the amount of difference is known to depend on the grating profiles and the geometric parameters of the gratings [19]. In the present work, the difference in the two frequencies Δf measured for various geometrical parameters of the slit array are (0.05 - 0.4) f_{SPP}.

In addition to the maximum transmission peak, there are also the transmission dips at about 11.59 and 22.37 GHz, where the transmittances are much lower than the transmittance of the single slit case. These dip positions are close to but shifted towards lower frequencies than the theoretically calculated SPP resonance frequencies of 12 and 24 GHz, which corresponds to the first and the second order of resonance, respectively, as can be seen in Figs. 2(b) and 2(c). Therefore, the transmittance is suppressed at the SPP resonance frequencies as theory predicts. However, the positions of the transmittance dips do not perfectly agree with the theoretically predicted values. We suspect that this difference may have been caused by several experimental conditions which are not as ideal as in the calculations. First, the calculations were performed in the two-dimensional space of infinitely periodic structures while the experiment was done with the three-dimensional finite structures. Second, in the calculations, the input source was incident at an exact normal, which is not true in the experiment as the incident beam from the antenna diverges while propagating to the aluminum sample. Third, in the Drude model, the expression for the permittivity of a metal contains a large imaginary part which means a loss term of aluminum in the microwave regime [27]. Thus from Eq. (3), the measured SPP resonance frequencies are expected to be shifted systematically towards smaller values. One notices that in Figs. 2(b) and 2(c) there exists a difference in the transmittance values in the higher frequency regime between the two calculated spectra. This may be due to the difference in the calculational methods between the FDTD and the analytical calculations which does not include the contributions from higher order transmittances. Therefore, the measured spectra usually show better agreement with the FDTD

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calculations than with the analytical calculations and this feature is well displayed in the following figures.

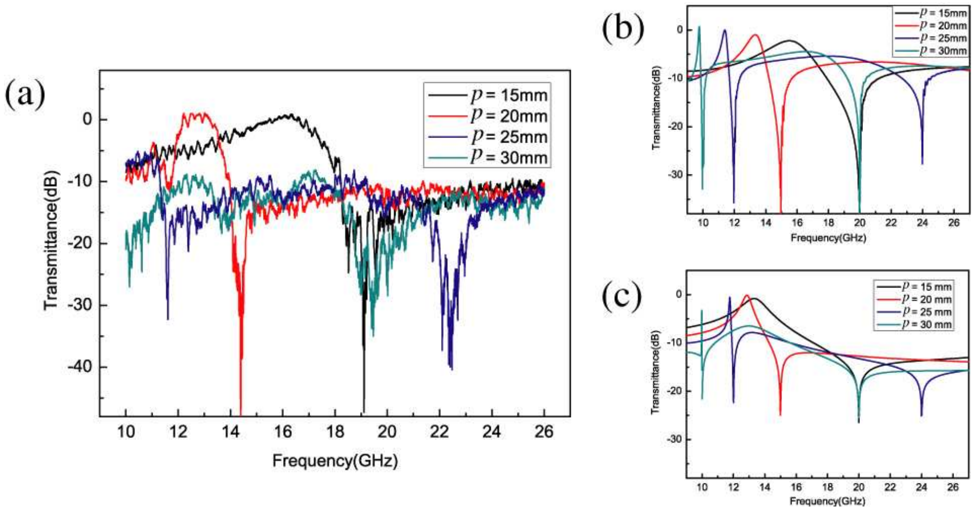

Fig. 3. (a) Measured, (b) FDTD calculated and (c) analytically calculated transmission spectra of slit arrays obtained by varying the slit periodicity p. The slit width a and the film thickness t are fixed at 4 mm and 6 mm, respectively.

As Eq. (1) contains all the geometrical factors for the transmittance explicitly, the transmission spectra can be obtained theoretically using both the analytical and FDTD calculations for various values of slit periodicity, slit width and film thickness. Figure 3 shows the measured and calculated transmittance spectra obtained varying the slit periodicity to 15, 20, 25 and 30 mm at a = 4 mm and t = 6 mm. It is expected from the SPP resonance condition that the positions of the transmittance peaks and dips will vary with the slit periodicity. The positions of the measured transmission dips reasonably agree with the calculated SPP resonance frequencies which are 20 GHz for p = 15 mm, 15 GHz for p = 20 mm, 12 and 24 GHz for p = 25 mm and 20 GHz for p = 30 mm. Therefore the transmission dip and peak positions are directly proportional to the slit periodicity and this result is very obvious considering the scaling property of Maxwell's equations.

In the measured results, it is observed that for the case of p = 15 and 20 mm, the transmission peaks exceeding unity exist at 16.31 and 12.78 GHz, respectively, which are in the lower frequency region than the first resonance dips. This means that the transmittance in this frequency region is larger than the reference value in the empty space and thus the transmittances are extraordinarily enhanced. This is possible in the experimental results because the sizes of the source and receiver antennas are so small compared with the size of aluminum plates that only small portion of the incident beam from the source antenna reaches the receiver antenna. Therefore, if the output beam through the slit array spreads only slightly less than the freely propagating beam directly from the antenna, the transmittance exceeding unity can be achieved. In comparison, the calculated peak values for slit arrays are always less than unity because the reference spectrum is obtained including all the input power.

Figure 4 displays the measured and calculated transmittance spectra obtained for the slit widths 3, 4 and 5 mm at t = 6 mm and p = 15 mm. In Eq. (2), the transmittance looks directly

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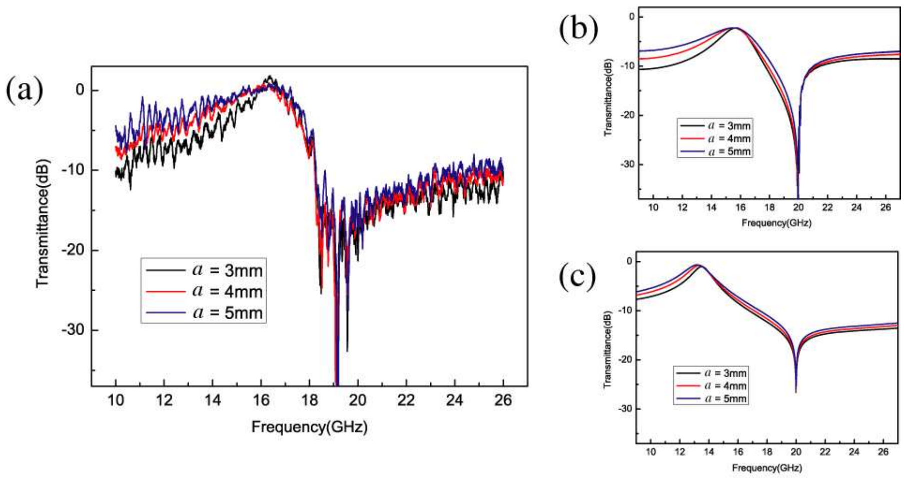

Fig. 4. (a) Measured, (b) FDTD calculated and (c) analytically calculated transmission spectra of slit arrays obtained by varying the slit width a. The slit periodicity p and the film thickness t are fixed to 15 mm and 6 mm, respectively.

proportional to the slit width due to the opening ratio a/p in T_0. However, W also includes the width factor and mainly depends on the ratio a/p, thus the a/p factor in T_0 is almost eliminated. Thus, all the spectra in Fig. 4 show that the position and intensity of the peaks are almost the same rather than directly proportional to the opening ratio a/p. Therefore, one can conclude that as the slit width increases, the maximum peak position and its intensity keep nearly the same values and only the peak shape gets slightly broader.

However, the two calculated results depicted in Figs. 4(b) and 4(c) are different in the maximum peak positions and also in the transmittance values. Because the diffracted angle for the lights of higher orders gets smaller as the frequency increases or the slit periodicity decreases, the differences between two calculations become larger at higher frequencies or at shorter slit periodicities. Also, one may estimate the influence of higher order transmittance to the transmission spectra from the difference between the two calculational methods. Though the exact maximum peak positions and intensities of measured spectra fit better to the FDTD calculations, the relative positions and broadness of the transmittance peaks for different slit widths are also exhibited in the analytical calculations.

Figure 5 shows the measured and calculated transmission spectra obtained varying the metallic films of thickness to 4, 6 and 8 mm at a = 4 mm and p = 15 mm. Experimentally measured maximum transmission peak positions are 17.47, 16.31 and13.81 GHz, for t = 4, 6 and 8 mm, respectively. The peak intensity of all peaks show almost 100% transmission and the peak positions display a considerable dependence on the metallic film thickness. This result also has a good agreement with the FDTD simulations in Fig. 5(b). Thus, the maximum transmittance frequency is largely affected by the metallic film thickness and moves toward lower frequencies as the film thickness increases.

Also, from the analytically calculated results of Eq. (1) depicted in Fig. 5(c), one can have some insight into the dependence of the maximum transmission on the metallic film thickness. In Eq. (1), the film thickness t appears only in the trigonometric functions in the dominator of T_0 and does not in the W factor. This indicates that the typical Fabry-Perot oscillations exist inside the slit. In the analytical calculation, $2kW$ is much larger than $1+k^2W^2$ in Eq. (1) and the transmission peaks are expected to exist when $\cos(kt)=0$, which means that $kt=\frac{2\pi}{\lambda}t=(n+\frac{1}{2})\pi$,

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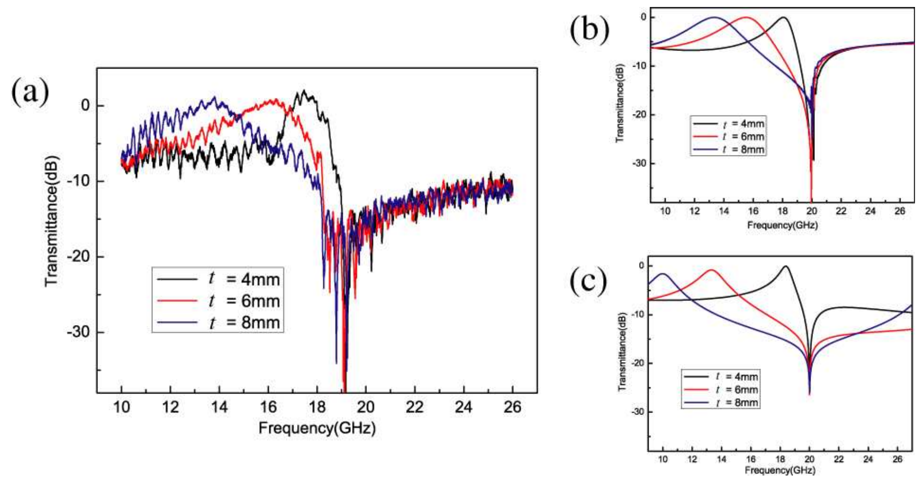

Fig. 5. (a) Measured, (b) FDTD calculated, and (c) analytically calculated transmittances of slit arrays with varying metallic film thickness. The slit periodicity p and the slit width a are fixed to 15 mm and 4 mm, respectively.

where n is an integer. Therefore, the positions of the transmission peaks are expected at the frequencies 18.75, 12.50, and 9.375 GHz for the aluminum film thickness of 4, 6, and 8 mm, respectively and the analytically calculated spectra support these results as can be seen in Fig. 5(c). Previously, in an experiment in terahertz regime,it was shown that this variation of the transmission peak position on the film thickness, independently of the slit width, periodicity and the incidence angle of light [20]. Though the maximum peak positions obtained from this analysis don't show a good agreement with the measured and the FDTD results displayed in Figs. 5(a) and 5(b) because of the missing higher order transmittance terms, one can understand the metallic film thickness is an important factor for peak transmission frequencies due to the Fabry-Perot oscillations inside the slits.

4. Conclusion

In summary, we have demonstrated the transmission properties of normally incident light through subwavelength slit arrays in metallic films at microwave frequencies both theoretically and experimentally. The extraordinarily enhanced transmission was clearly observed by the transmission peaks around the first SPP resonance frequencies and the highest value of the peaks is over 0 dB which means that almost 100% transmission was achieved in these frequencies in spite of small slit opening ratios a/p. Not only the enhanced transmission peaks, but also the transmission dips exist around the expected SPP resonance frequencies which mean that the transmission is surpressed at those frequencies due to the SPP resonance. All the transmission spectra could be satisfactorily explained by the SPP resonance - a generation of surface traveling waves through the coupling of the incident light to surface plasmon modes using the periodic slit array which acts like a grating coupler.

The dependence of the transmission peaks and dips on the geometrical parameters of the slit array is verified by measuring the transmission spectra varying the slit width, slit periodicity and the thickness of metallic film and obtained results show a good agreement with the FDTD calculated results. Also, the analytical calculations based on the zeroth-order diffraction of the TM polarized and normally incident beam was very helpful to understand the dependence of the transmission spectra on the geometrical parameters of slit arrays. Obtained results for the enhanced transmission of microwaves through subwavelength slit arrays can be applied to the technology of optical instruments such as sensors and optical filters based on the surface plasmon excitations.

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