Quantitative Measurement of Protein Using Metal Mesh Device

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Biosensing of protein adsorption with metal mesh device (MMD) was investigated by computational calculations and experiments. Electromagnetic field computation was carried out with a single unit cell of MMD. Equivalent circuit model of MMD on the single unit cell was assumed, and the biosensing with MMD was analyzed in detail by computational calculation and experimental measurements. The dip frequency of MMD was shifted by adsorption of protein on MMD. The shift of dip frequency of MMD was proportional to the amount of protein adsorption. The sensitivity of MMD biosensing was dependent on the microstructure of MMD, and proportional to the square of the dip frequency. The refinement of MMD structure can improve the sensitivity of protein detection.

Keywords Metal mesh device, terahertz spectroscopy, simulation, electromagnetic field analysis

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Introduction

Optics are promising technology for sensing based on the high sensitivity and label-free method. Though optical sensing with UV-visible light has been studied by many researchers, sensing technology in the terahertz region has not been studied enough. Currently, optical technology in the terahertz region is being energetically investigated. A metal mesh device (MMD) is a metal thin film with holes of sub-micrometer order arranged in a periodic manner (Fig. 1). The MMD has optical properties based on the periodic structures of microscopic holes.1–3 The MMD transmits electromagnetic waves of specific frequency (wavelength) in the terahertz region, corresponding to the period of the through holes, which act like a band-pass filter.4

The specific optical properties of MMD have been reported since the 1960s.5,6 MMD transmittance properties have been mainly studied, because the phenomena are related to surface plasmon resonance (SPR), from which the periodic structure of MMD originates.7 Before the recent developments in manufacturing technology, the shapes and the frequencies of MMD had been limited. In addition, the computational approaches such as electromagnetic field simulation had not been developed. Thus, the application of MMD has hardly been explored.

It was shown by Miyamaru et al.8 and Yoshida et al.9,10 that the transmittance property of an MMD changes with substance adsorption. They investigated the optical property change in view of dielectric property change.11 It was suggested that the amounts of the adsorbed substances are measured by optical property of MMD. This method is one of the potential label-free detection techniques. Of course, the representative label-free method is SPR like biacore. While SPR is highly sensitive, several drawbacks such as a short electromagnetic field from the surface and high cost are pointed out. Through the research on MMD manufacturing techniques, we have reported the fabrication of the MMD of various shapes, sizes, and transmittance properties. These achievements enabled low-cost devices with arbitrary detectable frequency range. We have been taking advantage of such improvements to develop new optical sensor technologies. In 2011, we reported the sensing principles of MMD in the sub-millimeter range,12 and the possibility of protein sensing adsorbed onto the MMD by the transmittance property in the terahertz (infrared) region.13–15

The MMD was manufactured with the electroforming method, which enables the fabrication of the devices of various structures, sizes, and transmittance properties of arbitrary frequency (wavelength). Therefore, it is possible to utilize the specific MMD corresponding to the target substances. Conversely, if MMD structures can be designed for the size and optical property of the target substance, the various targets are able to be sensed by MMD. Such a method has never been developed, and it would therefore be a novel optical measurement and detection method.

In the MMD detection techniques, the basic principles have not been clearly understood, though it has been suggested that

Fig. 1 Structure and physical properties of MMD: the representative image of MMD (left) and the dimension of MMD of f40, f100 and f150 (right).
the transmittance property of the MMD changes with the adsorbed dielectric material. In other words, previous studies have only shown a correlation between the change in transmittance frequency of an MMD, Δf [THz], and the concentration [nmol mL⁻¹] of the protein solution. The quantitative discussion for a basic characteristic of sensors has not been sufficient. Therefore, we investigated the basic property of MMD for sensing technology. This paper reports an electromagnetic field simulation of MMD and results of quantitative measurements of protein by MMD. We aim to study the MMD sensing technology through both computational theory and experiments.

Experimental

Preparation of MMD
The MMD was prepared by electroforming with nickel. Three types of MMD with different transmitted frequencies were prepared in this experiment. The MMD sample names, f40, f100, and f150, correspond to the devices with transmittance frequencies of 40, 100, and 150 THz, respectively. Each MMD consisted of a metallic thin film with square holes forming a periodic square lattice. Figure 1 shows the dimensions of the samples, where P [μm] is the lattice period, D [μm] the length of hole edge, and T [μm] the film thickness (Fig. 1). The electroforming method was used to make the MMD sample with Ni and outer diameter 6 mm. In order to improve the surface impedance, we used electrolysis deposition to coat the films with Au with thickness of a few tens of nm.

Transmittance spectroscopy of MMD
FT-IR (FT-IR Alpha, BrukerOptics, Ettlingen, Germany) was used to measure the transmittance properties of the MMD. The transmittance spectroscopies were measured before and after the surface modification of MMD. The change in the transmittance was determined from the difference between two measurements. The change was quantified in the frequency at the dip point in the passband, which is the bottom point of the transmittance waveform in a passband. The average value was determined by 8 replicate measurements.

Surface modification by streptavidin
In order to measure the optical response of MMD, the surface of MMD was modified by biotin as following procedure in Fig. 2. Briefly, Au was evaporated on Ni-MMD, and the samples were immersed in the ethanol solution of HS–(CH₂)₁₁–OH (ProChimia, Poland) (1 mg mL⁻¹) for 16 h at room temperature, immobilizing hydroxyl groups on the surfaces. Then, the samples were immersed in 3-aminopropyltrimethoxysilane (Wako, Tokyo) solution (1 wt%) for 3 h at 60°C. The consequent MMDs were immersed in 0.5 mg mL⁻¹ DMSO solution of N-succinimidyl (3-maleimidopropionate) (TCI, Tokyo) for 16 h at room temperature, immobilizing the maleimide groups on the surfaces. The MMDs were immersed in HS–(CH₂)₁₁–NH–CO–biotin (ProChimia) ethanol solution of 0.5 mg mL⁻¹ for 16 h at room temperature. The biotin immobilized MMD was immersed in streptavidin (Wako) PBS solutions of concentrations 0, 0.0189, 0.189 and 1.89 nmol mL⁻¹ for 2 h at 37°C. Streptavidin was the only protein used in this investigation. After immobilization of streptavidin, the MMD was washed sequentially with the buffer solution and water, and then dried in a dryer at 40°C overnight in order to inhibit the effect by water in protein.

Electrophoresis

The streptavidin was eluted from the substrate in 100 μL of 6 mmol Tris-HCl buffer (pH 6.8) for 5 min at 98°C. The eluted streptavidin was cast onto polyacrylamide gel (E-T12.5L) (ATTO Co., Tokyo) with molar mass 14 – 100 kDa and concentration 12.5%, and passing 50 mA of current at 250 V for about 1 h. The gel after the electrophoresis process was stained with SYPRO red for 30 min, and band images were obtained using a fluorescent scanner. The lanes of gel were assigned to

![Fig. 2 Procedure of biotin immobilization on Au-coated MMD: immobilization of (a) hydroxyl group with HS-(CH₂)₁₁–OH, (b) amino group with 3-aminopropyltrimethoxysilane, (c) maleide with N-succinimidyl (3-maleimidopropionate), and (d) biotin with HS-(CH₂)₁₁–NH-CO-biotin.](image_url)
the streptavidin solutions separated from the samples as well as to streptavidin solutions with known mass for calibration. The image analysis was conducted with Image-J and the detected lanes were compared with the standards. The mass was normalized by the area of the MMD’s principal plane to give the streptavidin mass per unit area of principal plane \( \text{ng mm}^{-2} \).

The measurement was conducted with 10 lanes, and the data was averaged.

**Electromagnetic field simulation**

The electromagnetic field was calculated with a software of CST Studio Suite (CST computer simulation technology, Framingham, MA). An MMD surface was modeled with adsorbed protein, and the transmittance property of the MMD was calculated by changing the thickness \( t \) of the imaginary material (Fig. 3). The figure shows a unit cell of an MMD, and calculations were conducted with periodic boundary conditions. The wave source was placed at the period \( P \) of MMD away from the MMD principal plane, and a plane wave was incident perpendicularly to the principal plane. The detector plane was placed at the period \( P \) of MMD away from the principal plane and on the side opposite to the source. The thickness \( t \) of the imaginary material was set to 0 (corresponding to no adsorption), 10, 20 and 30 nm, which was assumed to form the uniform thin layer on MMD. The physical properties of the imaginary material were set to be similar to protein; dielectric constant 3 and density 1 g cm\(^{-3}\), which was estimated by the average dielectric constant of amino acids and those of organic polymers. The imaginary part of the dielectric constant was assumed to be zero in order to simplify the calculation. The dielectric constant was assumed to be uniform in the entire THz region. The amount of the material was determined by calculating its volume from the material thickness \( t \) and its density.

In this simulation, only the surface current on MMD was calculated, where the current of the metal inside was not considered. The surface impedance of MMD was assumed as follows:

\[
Z = \frac{1}{\delta \times \sigma} \sqrt{\pi \times f \times \mu \over \sigma}
\]

where \( Z \), \( \delta \), \( \sigma \), \( f \) and \( \mu \) were interface impedance, thickness of the interface, conductivity, frequency, and magnetic permeability, respectively. Conductivity of MMD used was \( 1.2 \times 10^7, 1.0 \times 10^7 \) and \( 1.0 \times 10^7 \) [S/m] for 40, 100 and 150 THz, respectively. The conductivity was assumed based on that of the direct current measurement of Ni. The calculated value was the mass per unit cell, and the value was normalized by the area of the principal plane to calculate the mass per unit area of MMD principal plane [ng mm\(^{-2}\)].

The electromagnetic field of TE-11 mode was calculated with the model in Fig. 3. A small outshoot was set in the model to avoid the cancellation of dipole moment, where the dimension of the outshoot is \( 0.05 \times 0.05 \times T \) (Fig. 3(b)). It is assumed that the proteins adsorbed on the MMD as the uniform thin layer.

**Results and Discussion**

**Measurements and calculations of transmittance properties of MMD**

Transmittance spectra of MMD were measured with f40, f100 and f150 before the biotin immobilization (Fig. 4). This result showed that sample f40 has the passband around 40 THz with its central frequency at 38.888 THz (which is defined as the midpoint between the two 40% transmittance frequencies) and the dip frequency at 39.495 THz. MMD of f100 had the pass band around 100 THz, central frequency at 97.890 THz and dip frequency at 97.470 THz. MMD of f150 had the pass band around 150 THz, central frequency at 149.490 THz and dip frequency at 152.712 THz.

The structural parameters of \( P \), \( D \), and \( T \) (Fig. 1) were utilized to make the computational models in Fig. 3. No adsorption (material thickness \( t = 0 \text{ nm} \)) was assumed, and thus estimated
the transmittance properties of the samples before the surface modification. Then, the calculation results were compared with the measurements shown in Fig. 5. Table 1 shows the comparisons of the central frequency and the dip frequency between the measurement and the calculation as well as their error [%] for each sample. The error was calculated on the basis of measurement result. As an example, Fig. 5 shows the measured and calculated waveforms around the passband of sample f40. These results showed that the calculated and measured central frequencies and the dip frequencies matched within the maximum error of 1.87%, and that the transmittance waveforms around the passband were more or less identical. The validity of the calculated electromagnetic field and the experimental results on MMD was compared. Table 1 showed the comparisons between the calculated and the measured transmittance properties of f40, f100, and f150. Figure 5 shows representative data. These results showed that the calculation and the measurement matched around the passband, implying the validity of the computational model. Since a periodic boundary condition was supposed for the computational model, the diffraction of electromagnetic wave was not incorporated. From the results, the diffraction region was considered to be affected to the higher part of the pass band.

The dip in the spectra were specific phenomena in MMD, which have been reported by our group\cite{13,14,15} and other groups.\cite{8,9} The dip was the result of fano-like interference effect between the terahertz light transmitted directly and obliquely through MMD.\cite{16,17} The results suggested our simulation model with a small outshoot was valid for the fano-like interference and applicable for the MMD biosensing.

Distribution of the electric field and current of MMD

A dip frequency corresponds to a resonance based on the structure of MMD. Figure 6 shows the calculation results for the electric field and current distributions in a resonant condition at the dip frequency of f100. The computational results of resonant electric and magnetic fields of MMD at a dip frequency was based on the model with Fig. 3. The cancellation of the dipole moment was avoided by the addition of a small outshoot in Fig. 3(b), and the validity of the model was shown in the previous section.

One quarter of a whole cell was shown considering the MMD’s symmetry. The electric field distribution corresponded to the Z = 0 plane in Fig. 3(a). The current distribution corresponded to the MMD surface. The results show that the current flowed from the middle of one edge of the square hole to the middle of the other edge, and that its magnitude was zero around the edge centers and maximum at the corners. The electric field lines were directed in a concentric manner around the corner, and pointed from one edge to another. Its magnitude was maximum around the edge centers and zero at the corners. These electromagnetic distributions indicate that the hole with a small outshoot made a waveguide-like resonance, exciting a TE11-like mode as in a rectangular waveguide.

Equivalent circuit of MMD

Adsorbed protein on MMD induced the dip frequency shift. Figure 6 showed that TE11-like resonance mode of electromagnetic wavelength was excited at the dip frequency.

### Table 1: Comparison between the experimental and computational results for the central frequency and dip frequency for each MMD

| Band center frequency | Dip’s frequency | Error, % |
|-----------------------|-----------------|----------|
|                       | Measurement/THz | Calculation/THz | Error, % |
| f40                   | 38.89           | 38.81     | -0.19 |
| f100                  | 97.89           | 98.58     | 0.70 |
| f150                  | 149.49          | 153.34    | 1.87 |

Fig. 4 Transmittance IR spectra of MMD samples f40, f100, and f150.

Fig. 5 Comparison between experimental and computational waveforms around the dip frequency for MMD f40.

Fig. 6 Computational results for electric field and current distributions at the dip frequency of MMD sample f100.
To further understand the mechanism of biosensing, we carefully analyzed an MMD with equivalent circuit model. By placing inductance $L$ in the current path and capacitance $C$ in the electric field path, the corresponding resonance can be expressed in an equivalent circuit, as shown in Fig. 7. This equivalent circuit was an $LC$ parallel resonance circuit with the resonant frequency $\omega$ expressed in the below Eq. (1).

$$\omega = \frac{1}{\sqrt{LC'}}$$

where $L'$ and $C'$ signify the combined inductance and capacitance in the equivalent circuit, respectively. $C$ also can be expressed as follows Eq. (2).

$$C = \varepsilon \frac{S^2}{d}$$

where $\varepsilon$, $S$ and $d$ are the dielectric constant, the electrode area, and $d$ the distance between electrodes, respectively.

This equation shows the mechanism of the change in the dip frequency by protein adsorption. The protein adsorption increases the effective dielectric constant in the resonant space, which increases the $C$ component of the $LC$ parallel resonance and reduces the resonant frequency $\omega$ as a result. In the experiments, protein adsorption caused the dip frequency shift. The magnetic permeability of the organic substances is usually less than 1. The dip frequency shift from the inductance change can be ignored due to the small magnetic permeability.

As an example, Fig. 8 shows the change in the transmittance property around a dip frequency by the streptavidin adsorption on $f_{150}$, where streptavidin was used as a representative protein. The results in Fig. 8 fitted our equivalent circuit model in Fig. 7, which suggested that the change in dip frequency was based on the capacitance ($C$) in the TE11-like resonance.

**Computational results for biosensing of protein with MMD**

The computational model in Fig. 3 was applied to calculate the shift in the dip frequency of $f_{40}$, $f_{100}$ and $f_{150}$ by adsorption of imaginary material of protein on MMD. Using the dip frequency for $t = 0$ (no adsorption) as a reference, the shift in dip frequency $\Delta f_{\text{cal}}$ [THz] was calculated with adsorption of thickness $t$. We also calculated the protein amount [ng] from $t$ and normalized it to determine the mass of the imaginary material per unit area of the principal plane $M_{\text{cal}}$ [ng mm$^{-2}$]. Fig. 9(a) shows the relationship between the dip frequency shift ($\Delta f_{\text{cal}}$ [THz]), and the amount of the imaginary material per unit area of the principal plane $M_{\text{cal}}$ [ng mm$^{-2}$]. The results show that $\Delta f_{\text{cal}}$ of $f_{40}$ linearly increased with $M_{\text{cal}}$, and its slope was $6.36 \times 10^{-3}$ THz mm$^{-2}$ ng$^{-1}$. In the case of $f_{100}$, $\Delta f_{\text{cal}}$ also linearly increased with $M_{\text{cal}}$, and its slope was $4.08 \times 10^{-2}$ THz mm$^{-2}$ ng$^{-1}$. Similarly, in the case of $f_{150}$, $\Delta f_{\text{cal}}$ linearly increased with $M_{\text{cal}}$, and its slope was $1.09 \times 10^{-1}$ THz mm$^{-2}$ ng$^{-1}$.

![Fig. 7](image-url) The corresponding equivalent circuit model of an MMD’s unit cell at the dip frequency.

![Fig. 8](image-url) Change in the transmittance property of MMD sample $f_{150}$ before and after streptavidin adsorption.

![Fig. 9](image-url) Computational simulation results for (a) relationship between the mass of imaginary material and the shift in the dip frequency, and (b) relationship between the dip frequency and the sensitivity.
Experimental results for biosensing of protein by MMD

The transmittance spectroscopy was measured after the streptavidin-biotin immobilization, and the dip frequency shift ($\Delta f$ [THz]) was measured. Then, streptavidin was separated from MMD, and the actual amount of $M$ [ng mm$^{-2}$] was measured using electrophoresis. Figure 10(a) shows the relationship between $\Delta f$ [THz] and the streptavidin amount per unit area ($M$ [ng mm$^{-2}$]) of MMD. The result shows that, in the case of $f_{40}$, $\Delta f$ linearly increased with $M$, and its slope is $4.63 \times 10^{-3}$ THz mm$^2$ ng$^{-1}$. In the case of $f_{100}$, $\Delta f$ also linearly increased with $M$, and its slope is $2.59 \times 10^{-2}$ THz mm$^2$ ng$^{-1}$. Similarly, in the case of $f_{150}$, $\Delta f$ linearly increased with $M$, and its slope is $6.71 \times 10^{-2}$ THz mm$^2$ ng$^{-1}$.

The slopes in Fig. 10(a) can be defined as MMD’s measurement sensitivities, $A_{\text{dip}}$ [THz mm$^2$ ng$^{-1}$]. The plots in Fig. 9(a) show that a higher MMD passband corresponded to a higher sensitivity. In order to understand this relationship, we studied the correlation between the dip frequency without imaginary material, $f_{\text{dip,0}}$ [THz], and the sensitivity $A_{\text{dip}}$ [THz mm$^2$ ng$^{-1}$]. Figure 9(b) shows a plot expressing the relationship for each sample. These results shows that $A_{\text{dip}}$ was proportional to the square of $f_{\text{dip,0}}$, and the slope is $4.45 \times 10^{-6}$ mm$^2$ ng$^{-1}$ THz$^{-1}$.

The imaginary part of the dielectric constant of protein was assumed to be zero in this result (Fig. 9), but at the same time we found the imaginary part of the dielectric constants in the protein hardly affected the dip frequency (Table S1, Supporting Information). It is considered that the real part of the dielectric constant of the protein determined the dip frequency. The diversity of the real part of the dielectric constant in the protein was also studied, and the proportionality coefficient was dependent on the dielectric constants. The mass of protein adsorbed on MMD was still proportional to the square of the dip frequency (Fig. S2, Supporting Information). So far, the studies of the dielectric constants of organic substances in the THz frequency (Fig. S2, Supporting Information). The effect of water was removed by conducting the experiments in dry conditions, which helped the well-fitting of computational and experimental results.

Quantitative measurement of protein by MMD

The computational results in Fig. 9(a) showed the proportionality between the mass of imaginary material adsorbed to MMD and the change in the dip frequency, revealing that the frequency shift increases with increasing adsorbed protein mass. This indicates the validity of measuring the protein adsorbent mass on MMD by the dip frequency shift.

The spectroscopy shift was analyzed by the change in the resonant frequency of an LC parallel resonant circuit. While the resonant frequency was inversely proportional to the square root of $C$, it changed linearly in Fig. 9(a). Since the thin property of $t$ (0 – 30 nm) was significantly smaller than the size of the resonant space ($\mu$m, similar to the MMD’s structure parameter), $C$ to the power of $-0.5$ can be linearly approximated in this region.

Moreover, the experimental results in Fig. 10(a) showed that the shift in the dip frequency tended to linearly increase with the adsorbed mass of streptavidin on MMD, validating the calculations in Fig. 9(a). Based on the above, it is possible to quantify protein adsorbed to MMD, owing to the proportionality between the adsorbed mass on MMD and the shift in dip frequency of MMD. In this experiment, we eliminated the effect of water in the experiment and computational model, which resulted in the good agreement. A more realistic model and experiment in wet conditions is under investigation.

Sensitivity of quantification of protein by MMD

The computational results in Fig. 9(b) showed that the sensitivity was proportional to the square of the dip frequency. Since the dip frequency of MMD is accompanied by the structural refinement, the resonant space of MMD becomes small. Therefore, absorption of the same amount of imaginary material increases the occupying volume fraction in the resonant space in the single cell. This would, in turn, induced an effective increase in the dielectric constant in the capacitance ($C$), and thus in the shift of the resonant frequency. It was considered that the sensitivity can be improved by increasing the MMD’s dip frequency (by refining the MMD structure) and that it increases proportionally with the square of the dip frequency.
Also, the measurement results in Fig. 10(b) showed that the sensitivity tended to increase in proportion to the square of the dip frequency, validating the computational results in Fig. 9(b). The slopes were $4.45 \times 10^{-6}$ and $2.86 \times 10^{-6} \text{ mm}^2 \text{ ng}^{-1} \text{ THz}^{-1}$, which were the computational (Fig. 9(b)) and experimental (Fig. 10(b)) results, respectively. The experimental value was smaller than the calculated one. One possible main reason of the difference is the dielectric constants. The different dielectric constant changed the slope and the sensitivity of the sensor. Comparison between the computational and the experimental results suggested the dielectric constants below 3 (Fig. S2). Another possible reason is considered to be the protein adsorption mode. Though the protein was calculated as the uniform thin layer in the simulation, the protein adsorption seldom occurred uniformly, resulting in the difference of the experimental value from the calculation.

Conclusions

The quantification of protein mass measurement by MMD was investigated through experiments and computations. By an electromagnetic field simulation, we found that the change in the dip frequency monotonously increases with the mass of the imaginary material, and that the sensitivity increases proportionally with the square of the dip frequency (resonant frequency) of the MMD. In the experiments with streptavidin adsorption, we found that change in the dip frequency monotonously increases with the mass of streptavidin. The experimental results also agreed with the calculations that the sensitivity increases proportionally with the square of the dip frequency (resonant frequency) [THz] of the MMD.

Future work includes studying the MMD behavior with different proteins. SPR is generally known as a protein quantification method using resonance, as with MMD. While the resonance phenomenon is different between MMD and SPR, the protein mass quantification method is similar. In SPR, the same converting equation (relating resonant angle to mass of adsorbed protein) is used regardless of the protein type. This depends on the approximation that dielectric dispersion of protein in the visible frequency range is the same regardless of the protein type. We plan to determine if such a frequency range, where such approximation is valid, exists in the infrared range, which is used for MMD.

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Supporting Information

Data of electrophoresis, detailed simulation results are available in Supporting Information. This material is available free of charge on the Web at http://www.jsac.or.jp/analsci/.

References

1. Y. Strelniker and D. Bergman, Phys. Rev. B, 1999, 59, R12763.
2. L. Moreno, F. Vidal, H. Lezec, K. Pellerin, T. Thio, J. Pendry, and T. Ebbesen, Phys. Rev. Lett., 2001, 86, 1114.
3. F. Miyamaru and M. Hangyo, Appl. Phys. Lett., 2004, 84, 2742.
4. T. Ebbesen, H. Lezec, H. Ghaemi, T. Thio, and P. Wolff, Nature, 1998, 391, 667.
5. A. Mitsuishi, Y. Otsuka, S. Fujita, and H. Yoshinaga, Jpn. J. Appl. Phys., 1963, 2, 574.
6. R. Rawcliffe and C. Randa, Appl. Opt., 1967, 6, 1353.
7. H. Ghaemi, T. Thio, D. Grupp, T. Ebbesen, and H. Lezec, Phys. Rev. B, 1998, 58, 6779.
8. F. Miyamaru, S. Hayashi, C. Otani, K. Kawase, Y. Ogawa, H. Yoshida, and E. Kato, Opt. Lett., 2006, 31, 1118.
9. H. Yoshida, Y. Ogawa, Y. Kawai, S. Hayashi, A. Hayashi, C. Otani, E. Kato, F. Miyamaru, and K. Kawase, Appl. Phys. Lett., 2007, 91, 253901.
10. S. Yoshida, E. Kato, K. Suizu, Y. Nakagomi, Y. Ogawa, and K. Kawase, Appl. Phys. Express, 2009, 2, 012301.
11. M. Tanaka, F. Miyamaru, M. Hangyo, T. Tanaka, M. Akazawa, and E. Sano, Opt. Lett., 2005, 30, 1210.
12. T. Kondo, S. Kamba, K. Takigawa, T. Suzuki, Y. Ogawa, and N. Kondo, “Highly Sensitive Metal Mesh Sensors,” in Proceedings of Eurosensors XXV, ed. G. Kaltsas and C. Tsamis, 2011, 916 – 919.
13. H. Seto, C. Yamashita, S. Kamba, T. Kondo, M. Hasegawa, M. Matsuno, and Y. Ogawa, and Y. Miura, Langmuir, 2013, 29, 9457.
14. H. Seto, S. Kamba, T. Kondo, M. Hasegawa, S. Nashima, Y. Ehara, Y. Ogawa, Y. Hoshino, and Y. Miura, ACS Appl. Mater. Interfaces, 2014, 6, 13234.
15. H. Seto, S. Kamba, T. Kondo, Y. Ogawa, Y. Hoshino, and Y. Miura, Anal. Sci., 2015, 31, 173.
16. S. Nashima and Y. Ogawa, IEEJ Trans EIS, 2013, 133, 484.
17. T. Kondo, S. Kamba, K. Takigawa, T. Suzuki, Y. Ogawa, and N. Kondo, Procedia Eng., 2011, 25, 916.