Biosensing on a Plasmonic Dual-Band Perfect Absorber Using Intersection Nanostructure

Chung-Ting Chou Chao, Yuan-Fong Chou Chau,* and Hai-Pang Chiang*

ABSTRACT: Optical absorbers with multiple absorption channels are required in integrated optical circuits and have always been a challenge in visible and near-infrared (NIR) region. This paper proposes a perfect plasmonic absorber (PPA) that consists of a closed loop and a linked intersection in a unit cell for sensitive biosensing applications. We elucidate the physical nature of finite element method simulations through the absorbance spectrum, electric field intensity, magnetic flux density, and surface charge distribution. The designed PPA achieves triple channels, and the recorded dual-band absorbance reaches 99.64 and 99.00% nm, respectively. Besides, the sensitivity can get 1000.00 and 650 nm/RIU for mode 1 and mode 2, respectively. Our design has a strong electric and magnetic field coupling arising from the mutual inductance and the capacitive coupling in the proposed plasmonic system. Therefore, the designed structure can serve as a promising option for biosensors and other optical devices. Here, we illustrated two examples, i.e., detecting cancerous cells and diabetes cells.

1. INTRODUCTION

Plasmonic perfect absorbers (PPAs) based on surface plasmon polaritons (SPPs) effect serve a pivotal role in optical communication, filters, imaging, sensors.1−10 PPAs have attracted considerable attention for their fascinating characteristics due to the enhancing and absorbing electromagnetic (EM) waves in metal nanoparticles (MNPs) and their capability of the realization of highly integrated optical circuits (IOCs).11−17 The close relationship of the SPPs associated with the refractive index (RI) of the surrounding medium makes them become an available option for detecting the biomolecule, toxic liquid, and flammable gas.18−26 The narrow-FWHM (full width at half-maximum) PPAs can be utilized to detect RI materials since its unique optical property is very sensitive to environmental change.15,21−26 So far, many PPAs sensors have been proposed and achieved remarkable advances.21,27−38 Some of the previously reported PPAs concern the wavelength in the terahertz (THz).39 THz stands for the segment of the EM radiation between microwave and infrared ranging from 3 mm to 30 μm. This range is out of the wavelength range of biosensor application.40−42 Motivated by the penetration ability of near-infrared (NIR) light into tissue and the significantly lower light scattering and autofluorescence throughout the NIR spectral range, there is growing consideration of longer-wavelength biosensors based on PPAs in the NIR region (i.e., 700−1700 nm).4,40,43−45 Besides, achieving two or more absorption bands is required in many applications and has always been a challenge in visible and near-infrared (NIR) lights.

Narrowband PPAs can function as plasmonic sensors and other photonic devices.46−50 Various PPA structures had been designed to achieve narrow bands, but most of the structures were utilized on multilayer combined systems,29,51−53 which needs proper arrangement between layers in the practical fabrication process and encounters the challenge of manufacture.54,55 The PPAs with excellent optical absorption and sensing performance usually work in the infrared and visible regime.56 Although the multilayer metal−insulator−metal PPA could attain multiple channels in terahertz frequency for RI sensing application, their low sensing performance and complex geometries are still limited.57

In a PPA sensor, one essential issue for enhancing the light−matter interaction is to merge mixed metal’s surfaces, gaps, and cavities to facilitate enclosing SPPs modes, i.e., surface plasmon resonance (SPR), cavity plasmon resonance (CPR), and gap plasmon resonance (GPR).58−61 Many research groups employed different approaches to improving the sensor performance of PPA using the various parameters of materials and geometries and the hybridization of plasmonic EM wave coupling. Porous and tubulous metal nanostructure arrays have received considerable attention for the development of

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biosensors. Such structures have the advantages of opened surface morphology and can offer a suitable environment for label-free biosensing on the MNPs’ surfaces. In plasmonic MNPs, the metal surface could produce the SPR mode with an inductance effect, while the cavity and gap spaces could generate the GPR and CPR modes with a capacitance effect. These SPR, CPR, and GPR modes can dominate the hybridization of SPP modes for enhancing the sensing capability of PPA. Recently, several plasmonic sensors based on all-MNP structures have been proposed. However, these structures have fewer SPR and CPR coupling effects due to the lack of bridged intersection and resonated cavities in all-metal MNPs, limiting promising applications. Another approach has been proposed based on the Kretschmann configuration (KC). Arora et al. numerically and experimentally studied SPR sensors using plasmonic nanograting based on the KC. Elshorbagy et al. developed a plasmonic sensor using nanoslits and compared the mode of working wavelengths with the classical KC. Omidniaee et al. designed a Kretschmann-based glucose biosensor utilizing localized SPR of SiO$_2$/gold/silver-containing structure for the exact detection of glucose and sensitivity enhancement. The KCs, as mentioned above, show the drawback of fine-tuning the illumination of incident light and has a problem with precise detecting of SPR angle in an SPR-based biosensor. In addition, they have difficulty realizing IOCs highly due to the additional KC with the adhesion of prism on the substrate (i.e., a metal film bounded from one side by a prism and from the other side by air).

This work proposed a simple periodic structure including a closed loop and a linked interface for the near-unity absorption of dual-band EM waves in visible and NIR lights. We investigate and compare four patterns of PPAs, i.e., cases 1−4. A new type of proposed case 4 sensor structure based on a periodic array of four silver (Ag)-shell prisms linked with the intersection can provide an interaction of SPR between nanostructures and form a vital SPP source in the unit cell. The designed PPA with repeat unit cell is subject to periodic boundary conditions in the x- and y-axes and is opened in the z-axis in the free space environment, without the prism coupling problem like the KC. We use finite element (FEM) simulations to understand the mechanism of the nearly perfect absorption through the investigation of EM field and surface charge density distributions. The most sensitive zone inside the proposed PPA also can apply in gas or liquid sensing target. Under normal incidence, the absorbance is over 99% in modes 1 and 2 and over 60% in mode 3. The sensitivity of the designed case 4 structure can reach 1000 and 650 nm/RIU of mode 1 and mode 2 in the visible and NIR regime. Compared to the single-band high adsorption PPA, the dual band of high absorption PPA achieved by the designed structure has the advantages of two working windows, and one can select the desired operating wavelengths by varying the structural

Figure 1. Unit cells of the proposed PPA structures: (a) case 1, (b) case 2, (c) case 3, and (d) case 4 structures, respectively.
parameters. Thus, our design gives a straightforward strategy to achieve the desired dual-band PPA working from NIR to visible range. The proposed structure can apply in biomedical applications, e.g., detecting cancerous cells and diabetes cells. The article aims to find the strategy and guideline for designing a perfect plasmonic absorber (PPA) for sensitive biosensing applications.

2. SIMULATION MODELS AND FUNDAMENTAL

Figure 1a–d depicts the unit cells of the investigated cases 1–4. The plasmonic system was made up of hybrid-plasmon nanostructure composed of a periodic array of Ag prisms without (case 1) and with (case 2) a linked intersection, and Ag-shell prisms without (case 3) and with (case 4) a connected junction, placed on an Ag film with a silica (SiO2) as the substrate. The bottom Ag film plays a mirror role to block transmittance, which has a function of mirror layer. The unit cell of the PPA comprises three layers. The top surface is four Ag/Ag-shell prisms without an intersection nanostructure (case 1 and case 3) and with a connected intersection nanostructure (case 2 and case 4). The bottom Ag film deposits on a SiO2 layer. The structural parameters are the height of prism (h), the width of the prism (d), the thickness of Ag-shell (t), the period along x- and y-axes (P), and the thickness of the bottom Ag film (s). We used an available FEM-based commercial software, COMSOL Multiphysics,68,69 to model the simulations in a 3D model. Since the unit cell symmetry has the same spectral properties for x- and y-polarized incidences, we used the incident EM wave at normal incidence polarized in the x-axis from the top plane of the proposed structure. Periodic boundary conditions can consider in x- and y-directions to imitate an infinite array of the unit-cell system, and perfectly matching layers are applied along the z-direction to avoid EM wave’s reflections. The dielectric constant of Ag is fitted by the Drude–Lorentz model,70,71 and the RI of the SiO2 layer is n = 1.50. The absorptance can be expressed as \( A(\omega) = 1 - R(\omega) - T(\omega) \), where \( R(\omega) = 1 - S_{11}(\omega)^2 \) and \( T(\omega) = S_{11}(\omega)^2 \) stand for the reflectance and transmittance, respectively. Sensitivity (S) and figure of merit (FOM) are two essential factors for sensor design. We calculate S and FOM using \( S = \Delta \lambda / \Delta n \) (nm/RIU), RIU is an RI unit) and FOM = S/FWHM, where \( \Delta \lambda \) is the \( \lambda_{\text{res}} \) shift of transmittance and \( \Delta n \) is the difference in the RI corresponding to \( \lambda_{\text{res}} \). The full width at half-maximum (FWHM) can be defined as the bandwidth value connected to the left and right of the half-high position of the transmittance spectrum. Besides, we can obtain quality (Q) factor using \( \lambda_{\text{res}} / \text{FWHM} \). The damping strength (\( \Delta \Delta \)) describes the difference between the maximum and minimum transmittance, i.e., \( \Delta \Delta = (T_{\text{max}} - T_{\text{min}}) \times 100\% \).

Thanks to the rapid progress in nanotechnology, the designed PAA is compatible with the current manufacturing process using ion beam milling.73–76 Besides, spacer lithography can make uniformly patterned nanoshell arrays with sub-10 nm thicknesses.77,78

3. INSPECTION OF STRUCTURE’S MECHANISM AND PERFORMANCE

For simplicity, Table 1 directly shows the optimal geometrical parameters of the proposed structure. The optimal values of structural parameters, the arrangement, and the quantity of Ag-shell prisms in a unit cell are based on FEM simulations and our previous work.13 Based on FEM simulations (not shown here for simplicity), we found that four structural parameters, i.e., \( t, P, d, \) and \( h \), can tune the absorptance peak wavelengths ranging in visible to NIR wavelength, showing the feasibility and tunability of the designed structure. Figure 2a–d reveals the A/R/T spectra of the designed cases 1–4. The absorptance (A) can be calculated using \( A = 1 - R \) (reflectance) – T (transmittance). As seen, the discrepancy of peaks/dips of A/R/T ranges strongly depends on the different plasmon effects, including SPR, GPR, and CPR that happened in these structures. Since \( s = 100 \) nm, the T channel will prevent NIR light, and the absorptance will reduce to \( A \sim 1 - R \).

Based on curve shape and \( \Delta \Delta \), one can observe that only one available mode of A/R in case 1 (at \( \lambda_{\text{res}} = 1350 \) nm) and case 2 (at \( \lambda_{\text{res}} = 736 \) nm), two modes of A/R in case 3 (at \( \lambda_{\text{res}} = 793 \) and 608 nm), and three modes in case 4 (at \( \lambda_{\text{res}} = 1001, 727 \) and 591 nm), respectively. There is a significant difference in A/R between cases 1 and 4. The case 4 structure shows an excellent optical performance in terms of high absorptance peaks and \( \Delta \Delta \) among four cases. It is due to the four cavities in core—shell MNPs that can raise the CPR and GPR effects, and the connected intersection can offer a bridge to enhance the SPR among four Ag-shell prisms.79,80 We note that the two absorptance peaks of case 4 are nearly perfect (i.e., \( A = 99.64\% \) at mode 1 and \( A = 99.00\% \) at mode 2). The improved absorptance in the case 4 structure can intuitively attribute to one central intersection and four Ag-shell prisms, forming a higher plasmon resonance source than cases 1–3. The resulting SPPs in the unit cell center of the case 4 structure can offer dual-band near-unity absorptance and facilitate suppressing the intrinsic Ohmic losses in the proposed plasmonic system. By minimizing the reflectance and eliminating the transmittance, a perfect absorber is obtained, in principle. The physical rationation for these redshifts can ascribe to the effective increase in capacitance, and inductance of the resonant PPA81 leads to the rise in light—matter interaction in the plasmonic system. Table 2 summarizes the \( \lambda_{\text{res}} \) (nm), FWHM (nm), A (%) Q factor, and \( \Delta \Delta \) of the case 1–4 structures at their corresponding modes.

To get a deeper understanding of the physical mechanism, Figure 3a,b illustrates the \( x-y \) plane and \( x-z \) plane of electric field intensity (|E|, V/m) distributions at mode 1 for cases 1–4, respectively. The \( x-y \) plane intersects the central part of the metal prisms, while the \( x-z \) plane interests the middle height of the central row of metal prisms along the x-direction. The four metal prisms are for the minimization of reflectance by impedance matching, and the bottom Ag film is for blocking the transmittance. As observed in Figure 3a,b, most electric fields appear among the Ag/Ag-shell prisms and show strong SPR around the metal surfaces and edges, CPR inside the cavities, and GPR between the metal gaps. They exhibit a remarkable in-plane enhancement in E-field confinement in the gaps, deep holes, and metal intersection, and a significant out-plane enhancement following an edge enhancement surrounding their exterior sides. In addition, the pointy corner of Ag/Ag-shell prisms can provide an edge EM wave enhancement. The gaps and cavities in the case 4 structure serve as the SPPs

| Table 1. Default Structural Parameters of the Proposed Color Filter |
|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| P (nm) | h (nm) | d (nm) | w (nm) | g (nm) | t (nm) | s (nm) |
| 470 | 150 | 60 | 30 | 80 | 10 | 100 |
sources and generate the GPR and CPR modes, while the MNPs’ surfaces offer the SPR modes. The light–matter interaction in a unit cell can be ascribed to the E-field repetitive re-enclosure, thereby significantly increasing the resulting EM wave enhancement. These SPP modes could provide the constructive light–matter interference in case 4 structure, resulting in inductance and capacitance effects in the unit cell. Note that the case 4 structure shows a larger area of E-field distribution in x–y and x–z planes than those of other cases, which indicates that the coupling between the metal prisms and the bottom Ag film contributes to the dual-band perfect absorption.

The enhanced E-field distribution can be described by mapping the positive–negative (+ −) surface charge density distribution. Figure 4a,b shows the top view (left side) and three-dimensional (3D) view of surface charge density distribution (Coulomb/m²) of cases 1–4 at mode 1, respectively. In cases 1–4, the (+ −) charge pairs only spread on the metal surface, including the cross-linked veins, Ag/Ag-shell square prisms, and the bottom Ag film. Note that the case 4 structure undergoes the most extensive charge pairs

### Figure 2. Absorptance (A), reflectance (R), and transmittance (T) spectra of the designed PPAs: (a) case 1, (b) case 2, (c) case 3, and (d) case 4, respectively.

### Table 2. λ_{res} (nm), FWHM (nm), A (%), Q Factor, and ΔD of the Case 1–4 Structures at Their Corresponding Modes

| mode | case 1 | case 2 | case 3 | case 4 | case 4 |
|------|--------|--------|--------|--------|--------|
|      | 1      | 1      | 2      | 1      | 2      |
| λ_{res} (nm) | 1350   | 736    | 793    | 608    | 1001   |
| FWHM (nm)    | 50     | 80     | 90     | 35     | 45     |
| A (%)        | 33.33  | 83.07  | 96.48  | 54.85  | 99.64  |
| Q factor     | 27.0   | 9.20   | 8.81   | 17.37  | 22.24  |
| ΔD (%)       | 30.78  | 79.95  | 93.24  | 32.6   | 95.82  |

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distribution on the metal surface among all cases. Significantly, the dipole-like charge pattern in the case 4 structure’s surface can be simultaneously governed by the hybridization of SPR, GPR, and CPR modes. The central intersection plays a pivotal role in bridging the (+ −) charge pairs in a plasmonic system, offering a more substantial dipolar effect and strong mutual

Figure 3. Electric field intensity (|E|, V/m) distributions at (a) x−y plane and (b) x−z plane of mode 1 for cases 1−4, respectively.

Figure 4. Surface charge density distribution (Coulomb/m²) at (a) top view (left side) and (b) 3D view of cases 1−4 at mode 1, respectively.
inductance on metal surfaces and capacitive coupling in resonant cavities.

To investigate the sensing performance of proposed cases 1–4 structures, Figure 5a–d examines the absorptance spectrum response to the variation of ambient RI \( (n = 1.1, 1.3, \text{ and } 1.5) \) for case 1–4 structures, respectively. The selected \( n \) values are for the testing purpose, and this range is suitable for gas and liquid samples. As observed, there is a remarkable redshift of each mode under the variation of RI. When the ambient \( n \) values rise from 1.1 and 1.3 to 1.5, one can see a clear redshift, and \( \lambda_{\text{res}} \) shifts from 1480 to 2010 nm for mode 1 of case 1; 800 to 1080 nm for mode 1 of case 2; 660 to 1160 nm for mode 1; 660 to 860 nm for mode 2 of case 3; and 1100 to 1500 nm for mode 1, 790 to 1050 nm for mode 2, and 760 to 840 nm for mode 3 of case 4, respectively. Therefore, the recorded \( S \) and FOM are 1325 nm/RIU and 12.05 1/RIU for modes 1–2 of case 3; and 1000 nm/RIU and 10.00 1/RIU, 650 nm/RIU and 10.83 1/RIU, and 200 nm/RIU and 5.00 1/RIU for modes 1–3 of case 4, respectively. We found that case 1 has the most significant value of sensitivity among all examples. However, the low \( \Delta D \) and absorptance will limit its application. It should be noted that the case 4 structure (Figure 5d) possesses the merits of a narrow FWHM, a nearly perfect absorptance (\( A = 99.05\% \) in mode 1 and \( A = 99.46\% \) in mode 2), and a high \( \Delta D \) keep in this RI range. These factors are crucial factors for high sensing performance. This outstanding feature of the case 4 structure paves the way to the possible applications in IOCs and nanophotonics devices.

4. BIOSENSING APPLICATION

Based on the above analysis, we can conclude that the proposed case 4 structure is the best choice for biosensing.
application among cases 1–4 because the obtained dual perfect absorptance peaks are in the wavelength of NIR light. For sensing applications, the surrounding medium can measure on the top surface of the case 4 structure. Here, we show two sensing applications, the surrounding medium can measure absorptance peaks are in the wavelength of NIR light. For general, testing diabetes involves pain and bleeding.86 and insulin generation cannot act in its regular function. In cancerous cells. Diabetes is a metabolic disorder in the body, and the healthy base cells with an RI of 1.36. Figure 6 displays the absorptance spectrum for normal diabetes cell (n = 1.35), diabetes cell (n = 1.41), normal basal cell (n = 1.36), and cancerous cell (n = 1.38) in the wavelength range of 800–1800 nm.

Table 3. λ_res (nm), Absorptance (A, %), FWHM (nm), QF, D (%), S (nm/RIU), and FOM (1/RIU) of Case 4 Structure for Normal Diabetes Cell (n = 1.35), Diabetes Cell (n = 1.41), Normal Basal Cell (n = 1.36), and Cancerous Cell (n = 1.38) Corresponding to Mode 1 and Mode 2 in the Wavelength Range of 800–1800 nm

| RI  | mode | λ_res (nm) | A (%) | FWHM (nm) | QF  | D (%) | S (nm/RIU) | FOM (1/RIU) |
|-----|------|------------|-------|----------|------|-------|------------|-------------|
| 1.35 | mode 1 | 1333 | 98.97 | 100 | 13.30 | 95.00 | ref | ref |
|     | mode 2 | 952 | 99.72 | 80 | 11.88 | 77.3 | ref | ref |
| 1.41 | mode 1 | 1391 | 98.84 | 100 | 13.90 | 93.29 | 1000 | 10.00 |
|     | mode 2 | 991 | 99.74 | 80 | 12.36 | 77.16 | 650 | 8.13 |
| 1.36 | mode 1 | 1343 | 98.95 | 100 | 13.40 | 98.40 | ref | ref |
|     | mode 2 | 958 | 99.73 | 70 | 13.68 | 77.27 | ref | ref |
| 1.38 | mode 1 | 1362 | 98.91 | 100 | 13.60 | 98.00 | 1000 | 10.00 |
|     | mode 2 | 971 | 99.73 | 80 | 12.14 | 75.57 | 650 | 8.13 |

The light–matter interaction arising from the linked intersection plays a vital role in absorbing mode 1 (larger wavelength) and mode 2 (shorter wavelength). The distribution of (+−) charge pairs depends on the resonance condition arising from the interaction between incident light and case 4 structure, which shows different surface charge density distributions on the metal surface. As seen in Figure 7a,b, there is a powerful electric dipole resonance at four arms of the central intersection due to the accumulation of charges on both sides of the Ag-shell prisms, resulting in violent magnetic resonance in case 4 structure.96,97 At resonance modes (see the left and middle panels of Figure 7a,b), the surface charge density distributed inside the interior walls of Ag-shell prisms are much higher than those of off-resonance modes (see the perfect absorption in the NIR region. As seen in Table 4, our designed PPA demonstrates a dual-band of high absorption with acceptable values of S and FOM and has the advantages of two working windows and the flexibility of selecting desired operating wavelengths in the NIR range. We noted that the published PPAs in Table 4 could not implement the coupling effect between Ag-shell prisms due to the absence of an intersectional connection.

To get more insight into the physical nature, Figure 7a,b shows the selected distributions of magnetic flux density lines (in cyan lines, in the unit of Tesla) and a 3D view of surface charge density distribution (in the unit of C/m²) corresponding to mode 1 and mode 2, and one of off-resonance modes (at λ_res = 1800 nm) for n = 1.35 and n = 1.41 of case 4, respectively. The light–matter interaction arising from the linked intersection plays a vital role in absorbing mode 1 (larger wavelength) and mode 2 (shorter wavelength). The distribution of (+−) charge pairs depends on the resonance condition arising from the interaction between incident light and case 4 structure, which shows different surface charge density distributions on the metal surface. As seen in Figure 7a,b, there is a powerful electric dipole resonance at four arms of the central intersection due to the accumulation of charges on both sides of the Ag-shell prisms, resulting in violent magnetic resonance in case 4 structure.96,97 At resonance modes (see the left and middle panels of Figure 7a,b), the surface charge density distributed inside the interior walls of Ag-shell prisms are much higher than those of off-resonance modes (see the
right panels of Figure 7a,b). Note that the magnetic flux density lines at resonant mode 1 and mode 2 are much denser than their off-resonance modes, revealing that the high density of spiral streamlines enclosed the Ag-shell prisms along the x-direction for mode 1 and toward the y-direction for mode 2. This feature leads to the strong absorption of incident light and the enhancement of the coupling magnetic field, resulting in close interaction with the proposed case 4 structure. Thus, we can deduce that the surface current can transmit through the central intersection nanostructure. On the contrary, the magnetic density flux lines across the case 4 structure are upright, showing less interaction with the case 4 design at off-resonance modes.

5. CONCLUSIONS
In summary, we proposed a plasmonic nearly perfect absorber based on a compact structure that consists of a closed loop and a linked intersection in a unit cell for sensitive biosensing applications. We clarified the physical mechanism through the absorbance/reflectance/transmittance spectra and distribution of electric field intensity, magnetic flux density, and surface charge distribution based on a 3D simulation model of FEM. The designed PPA can achieve triple-resonance mode in visible and NIR lights, and the recorded dual-band absorptance can reach 99.64 and 99.00%, respectively. Besides, the sensitivity can get 1000.00 and 650 nm/RIU for mode 1 and mode 2, respectively. The strong narrowband absorption results from the electric and magnetic resonance resulted in the mutual inductance and the capacitive coupling in the unit cell of PPA. The metal surface in the unit cell could offer the SPR mode with an inductance effect, while the cavity and gap spaces in the unit cell could induce the GPR and CPR modes with a capacitance effect. The previously reported PPA structures cannot achieve such a coupling effect in their design due to the absence of Ag-shell prisms with a closed loop and a connected junction between them. The proposed structure can be applied in biomedical applications, e.g., detecting cancerous cells and diabetes cells. This work provides a novel idea for the future research of a perfect metamaterial absorber and has excellent potential as a biosensor.

■ AUTHOR INFORMATION
Corresponding Authors
Yuan-Fong Chou Chau — Centre for Advanced Material and Energy Sciences, Universiti Brunei Darussalam, Gadong BE1410, Brunei Darussalam; Email: chou.fong@ubd.edu.bn
Hai-Pang Chiang — Department of Optoelectronics and Materials Technology, National Taiwan Ocean University, Keelung 20224, Taiwan; orcid.org/0000-0003-0752-175X; Email: hpchiang@mail.ntou.edu.tw

Author
Chung-Ting Chou Chao — Department of Optoelectronics and Materials Technology, National Taiwan Ocean University, Keelung 20224, Taiwan
Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c05714

Notes
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