Optical Nanodipole and Nanospiral Antennas

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***Abstract*—The antenna impedance of a nanodipole can be matched to a metal-insulator-metal (MIM) waveguide impedance by the aid of a shunt stub connected at the feed point. Generation of a circularly polarized wave is numerically demonstrated by a rectangular spiral structure fed by the MIM waveguide.**

***Index Terms*—Characteristics impedance, Optical antennas, Impedance matching, Circularly polarized wave.**

I. Introduction

Nanoantennas operating at infrared and visible wavelengths, analogues of microwave and radiowave antennas, are one of the interesting and exciting areas of plasmonic phenomena [1]-[5]. A metal-insulator-metal (MIM) waveguide may be a practical candidate for feeding the nanoantennas. Note that the metal is not a perfect conductor at optical wavelengths. Therefore, it is an important task to study to what extent the knowledge obtained from the conventional transmission line and antenna theories hold true at optical antennas.

In this article, we first consider a nanodipole antenna fed by the MIM waveguide. Tuning is successfully carried out by the aid of a shunt stub circuit without using a lumped element [6]. Secondly, generation of a circularly polarized (CP) wave is studied using a rectangular nanospiral antenna. Calculation shows that the CP wave is retained over a wide wavelength range, similar to the spiral antenna at microwave frequencies. The frequency-dependent FDTD method based on the trapezoidal recursive convolution technique [7] is adopted for the present investigation.

II. Nanodipole Antenna with a Stub

The configuration of a nanodipole with a shunt stub is illustrated in Fig. 1. The dipole arms and feeding MIM waveguide are made of silver rods with a square cross-sectional shape having a width of $w = 20$ nm. A gap length between the two rods is taken to be $g = 12$ nm. The total dipole arm length is chosen to be $l_{\mathrm{d}} = 160$ nm. The refractive index of silver, n_{m} [8], is assumed to be expressed using the Drude-Lorentz model. An operating wavelength is fixed to be 700 nm.

Since the metal is not perfectly conducting at optical frequencies, we cannot rigorously evaluate the characteristic impedance of the MIM waveguide, in contrast to that at microwave frequencies. However, the characteristic impedance may be approximately evaluated by the conventional technique, since the longitudinal field components are sufficiently small, so that the MIM waveguide can be regarded as a quasi-TEM line. We, therefore, estimate the characteristic impedance

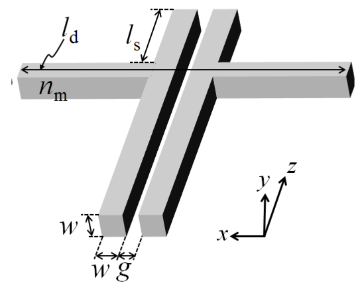

Fig. 1. Nanodipole antenna with a shunt stub.

using the following equation [9]:

$$Z = \frac{V}{I} = \frac{\int_{-g/2-w/2}^{g/2+w/2} \boldsymbol{E} \cdot d\boldsymbol{l}}{\oint \boldsymbol{H} \cdot d\boldsymbol{l}} \qquad (1)$$

in which the eigenmode fields are determined by the Yee-mesh-based imaginary distance beam-propagation method [10]. To the best of our knowledge, this is the first attempt to evaluate the characteristic impedance of a three-dimensional plasmonic waveguide. Calculation shows that the characteristics impedance of the MIM waveguide is $420 - j3\ \Omega$ for the silver metal, while 100 Ω for the perfect conductor.

The impedance matching at the feed point of the nanodipole antenna is important for efficient power transfer. It is well-known that the input impedance can be uniquely determined from a knowledge of the standing-wave ratio of voltage or current and the distance between the voltage or current minimum and the reference point at which the impedance is desired. We adopt this traditional technique to obtain the input impedance of the optical nanodipole antenna.

Since the ratio of l_{d} to w is relatively small, appreciable capacitance seems to appear at the feed gap. Calculation, however, shows that the input impedance of the present nanodipole is inductive. It follows that additional capacitance is required to realize the conjugate matching. For this purpose, we introduce an open-circuited stub, which consists of the same rod as the dipole and the waveguide. Fig. 2 shows the reflectivity as a function of stub length l_{s}. It is worth mentioning that the reflectivity is significantly reduced for $l_{\mathrm{s}} \approx 20$ nm.

III. Nanospiral Antenna

Another topic of interest in optical antennas is to generate a CP wave. By analogy with microwave antennas, we will consider the rectangular nanospiral antenna shown in Fig. 3, in which the silver rods with $g = 20$ nm are employed for the MIM waveguide, and those with $w = 40$ nm for the spiral arms. The field ($\sqrt{|E_x|^2 + |E_y|^2}$) distribution observed in the spiral plane is illustrated in Fig. 4, in which the wavelength

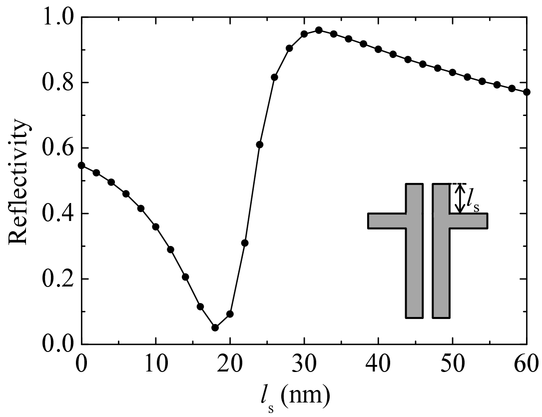

Fig. 2. Reflectivity as a function of stub length l_s.

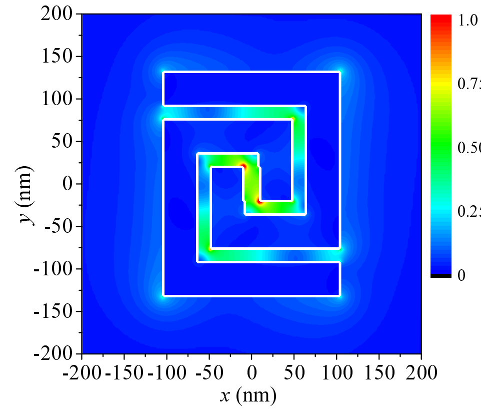

Fig. 4. Field distribution at λ = 700 nm.

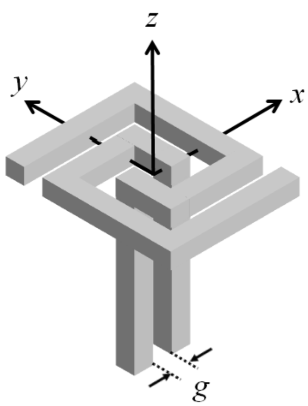

Fig. 3. Nanospiral antenna.

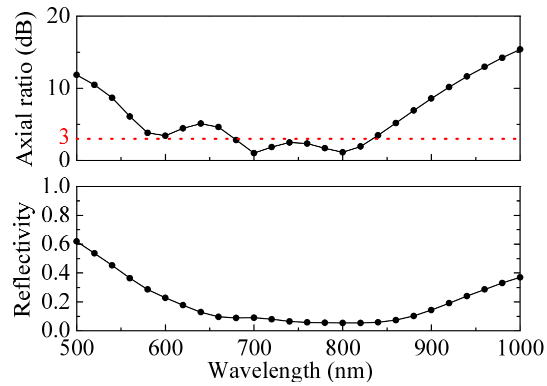

Fig. 5. Reflectivity and axial ratio as a function of wavelength.

is taken to be 700 nm. It is seen that the traveling-wave field is generated in the gap between the metal arms, resulting in a CP wave.

Fig. 5 shows the reflectivity and axial ratio (AR) as a function of wavelength. It is found that reflectivities of less than 0.1 is achieved over a wavelength range of 680 to 820 nm, where a radiation efficiency of larger than 0.95 is retained. It should be noted that the impedance matching is fairly good over a wide frequency range without using any additional matching technique, such as a stub circuit. Furthermore, a CP wave is successfully generated: an AR of less than 3 dB is obtained over the same wavelength range.

IV. Conclusion

The antenna impedance of an optical nanodipole is successfully matched to that of the MMI waveguide by the aid of a shunt stub. In addition, by analogy with microwave antennas, a radiator of a circularly polarized wave is demonstrated using a rectangular nanospiral structure. An axial ratio of less than 3 dB is obtained over a wide wavelength range, where the impedance matching is achieved without using any additional technique.

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