Actively tunable bistable optical Yagi-Uda nanoantenna

Ivan S. Maksymov,∗ Andrey E. Miroshnichenko, and Yuri S. Kivshar
Nonlinear Physics Centre and Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS), Research School of Physics and Engineering, The Australian National University, Canberra, ACT 0200, Australia

∗mis124@physics.anu.edu.au

Abstract: We propose and theoretically demonstrate a novel type of optical Yagi-Uda nanoantennas tunable via variation of the free-carrier density of a semiconductor disk placed in a gap of a metallic dipole feeding element. Unlike its narrowband all-metal counterparts, this nanoantenna exhibits a broadband unidirectional emission and demonstrates a bistable response in a preferential direction of the far-field zone, which opens up unique possibilities for ultrafast control of subwavelength light not attainable with dipole or bowtie architectures.

© 2012 Optical Society of America

OCIS codes: (250.5403) Plasmonics; (190.1450) Bistability; (310.6628) Subwavelength structures, nanostructures.

References and links


1. Introduction

Owing to recent advances in nanotechnology, plasmonic nanoantennas have become a subject of considerable theoretical and experimental interest [1,2]. Plasmonic resonances in nanoantennas allow breaking through the fundamental diffraction limit [3], opening up novel opportunities for controlling light–matter interactions within subwavelength volumes. Several potential applications of nanoantennas have been considered in topics such as spectroscopy and high-resolution near-field microscopy [2], subwavelength light confinement and enhancement [4], photovoltaics [5], sensing [6], molecular response enhancement [7], non-classical light emission [8], and communication [9].

In many of these applications, controlling and modifying the far-field of a nanoantenna is an important issue that is particularly interesting for obtaining directional beaming effects, which have been demonstrated e.g. with Yagi-Uda architectures [10–14]. However, an efficient nanoantenna must not only have a large local field enhancement and a high directivity [15] but also be wavelength tunable over a wide spectral range [16] because it allows a smaller nanoantenna to behave as a larger nanoantenna or as an array of nanoantennas [13], both saving space and improving performance.

Consequently, a large and growing body of research investigates tunable nanoantennas [17–24]. Many novel control mechanisms try to exploit the concept of metamaterial-based [25] and non-Foster impedance matching circuits [26], where one of the possible ways for achieving spectral tuning is based on the use of tunable nanocapacitors and/or nanoinductors [27,28]. Other approaches may rely on vanadium oxide tunable metamaterials [29], mechanically reconfigurable photonic metamaterials [30] or metamaterials hybridized with carbon nanotubes [31]. Large spectral tunability can also be obtained using electrically controlled liquid crystals [32–34], but a very slow response of liquid crystals is not suitable for many application and, in general, a solid-state implementation is more suitable for on-chip integration of nanoantennas.

However, the spectral tuning of optical Yagi-Uda nanoantennas has not been yet demonstrated because their capability to tune to multiple operating frequencies is compromised by their ability to receive and transmit light in a preferential direction (their operating bandwidth is limited to just a few percents around the designed resonance frequency). Tunable Yagi-Uda nanoantennas could have technological applications in building broadband optical wireless communication systems, advanced nano-sensor systems, high performance solar cells as well as wavelength tunable single photon sources and detectors.

In this paper, we suggest to exploit the free carrier nonlinearity of semiconductors for a dynamical tuning of the operating wavelength of a plasmonic unidirectional Yagi-Uda nanoantenna consisting of silver nanorods used for the feeding element, reflector and directors. We modify the feeding element as compared with previous designs [11] and consider a semiconductor nano-disk squeezed by two identical nanorods. The illumination of the feeding element with a laser beam alters the conductivity of the nano-disk and enables a monotonic tuning of the operating wavelength of the nanoantenna in a very wide spectral range as compared with that of conventionally designed Yagi-Uda nanoantennas [11–14].

Most importantly, the nanoantenna combines the capability of controlling light at the nanoscale with a bistable response in the far-field zone. Optical bistability is a fundamental...
Fig. 1. A tunable plasmonic Yagi-Uda nanoantenna consisting of silver nanorods used for reflector, feeding element and directors. The yellow area of the feeding elements corresponds to the semiconductor nano-disk used as loading. The nanoantenna is surrounded by air. The semi-transparent red arrow schematically shows the direction of the incident plane wave.

physical phenomenon that makes it possible to realize all-optical switching, optical limiting, logic gating and amplification of light pulses [35]. The realization of all-optical operations with a nanoantenna can without doubt be regarded as a big step toward creating novel ultra-fast subwavelength optical devices capable of manipulating and transmitting light pulses to, from and between nanoemitters.

2. Design and simulation model

The core design and interpretation of the results are performed using CST Microwave Studio software implementing a Finite Integration Technique. Figure 1 shows a plasmonic Yagi-Uda nanoantenna consisting of metal nanorods used for reflector, feeding element and directors. Without loss of generality, in this work we choose silver as the metal because it has the smallest optical losses of any natural metal in the visible and IR spectrum [36]. Owing to its relative lower loss, gold can be used instead of silver, which makes our nanoantenna more attractive for biomedical and sensor applications. The elements of the nanoantenna could also be made of nickel. The simultaneous ferromagnetic and plasmonic dual functionality of nickel nanoantennas opens up novel opportunities for magnetic manipulation of light [37].

The optimal length of the nanorods was designed relying on the effective wavelength rescaling principle [2], which takes into account the volume of the nanorods and absorption losses in silver. According to this approach, the resulting reduced effective wavelength $\lambda_{\text{eff}}$ ‘seen’ by the nanoantenna is related to the incident wavelength $\lambda$ by a simple relation $\lambda_{\text{eff}} = n_1 + n_2 \left( \frac{\lambda}{\lambda_p} \right)$, where $n_1$ and $n_2$ are some coefficients with dimensions of length and $\lambda_p$ is the plasma wavelength. The predictions of the rescaling approach were confirmed by means of full-vectorial 3D numerical simulations.

We optimize the nanoantenna performance for a central wavelength to be $\approx 1 \mu m$. We choose the radii of the nanorods and those of their outer rounded edges as $r = 25$ nm, and the spacing between all elements as $w = 30$ nm [15]. The feeding element consists of two nanorods with non-rounded inner edges, separated by a semiconductor nano-disk. The total length of the feed-
ing elements including the nano-disk is $L = 390 \text{ nm}$. The lengths of the reflector and directors are chosen as $1.125L$ and $0.75L$, respectively. We assume that the nano-disk of the feeding element is made of amorphous silicon (a-Si) and that its width constitutes 50 nm. The nanoantenna is surrounded by air because this provides the simplest model to which additional elements of any practical design, such as e.g. a substrate, can be added.

A change in the dielectric permittivity of the nano-disk loading of the feeding element caused by an increase in the free carrier density is modelled using a Drude model based on experimental values $\varepsilon_{\text{exp}}(\omega)$ of a-Si [36] as

$$
\varepsilon(\omega) = \varepsilon_{\text{exp}}(\omega) - \left( \frac{\omega_p}{\omega} \right)^2 \frac{1}{1 + \frac{1}{\omega \tau_D}},
$$

where $\omega_p = \sqrt{Ne^2/\varepsilon_0 m_{\text{opt}}^* m_e}$ denotes the plasma frequency, with $N$ the free carrier concentration, $m_{\text{opt}}^* = (m_e^{* - 1} + m_h^{* - 1})^{-1}$ the optical effective mass of the carriers, and $\tau_D = 10^{-14} \text{ s}$ the Drude relaxation time. The optical effective mass for a-Si, $m_{\text{opt}}^* = 0.17$, is estimated to be close to the value of crystalline silicon [20].

3. Results and discussion

To start with, we investigate near- and far-field zone characteristics of the Yagi-Uda nanoantenna. As we aim at achieving a gradual spectral tuning, we consider the free carrier density in between 0 and $3 \cdot 10^{21} \text{ cm}^{-3}$, that is in the range where the feeding elements gradually transfers from a capacitive mode to a partially conductive one in particular frequency range. The nanoantenna is illuminated with a linearly polarized plane wave (the electric field is orientated along the $y$-coordinate) incident from the rear end of the nanoantenna under the angle of 45 degrees as shown in Fig. 1.

The top panel of Fig. 2 shows the power emitted by the nanoantenna in the maximum emission direction designed to align with the $x$-axis. The bottom curve was calculated for the free carrier density of $0 \text{ cm}^{-3}$ whereas the others were calculated for the free carrier densities gradually increasing up to $3 \cdot 10^{21} \text{ cm}^{-3}$. In all curves we observe three main maxima, but also some others related to higher order mode interactions. Since the nanoantenna is designed to perform around the wavelength of 1 $\mu$m, we first investigate the resonances occurring in this region. We notice that an increase in the free carrier density produces a monotonic decrease in the operating wavelengths from 1.07 $\mu$m (denoted as A in Fig. 2) to 0.84 $\mu$m (denoted as A') also accompanied by a weak decrease in the power emitted by the nanoantenna.

In order to confirm that in this range the feeding element is in its resonance as should be in the case of a Yagi-Uda antenna [14], in the bottom panel of Fig. 2 we plot stationary distributions of the electric field $|E|$ in the near-field zone of the nanoantenna. As shown in sub-panels A and A' (here A corresponds to 0 $\text{ cm}^{-3}$ and A' to $3 \cdot 10^{21} \text{ cm}^{-3}$), the feeding element is at its maximum field strength brighter than all the other elements.

These results demonstrate that the resonance wavelength of the A–A' resonances is gradually blue-shifted due to decrease of the permittivity in that particular frequency range. It results in possibility to gradually tune the resonant response of the nanoantenna in a 230 nm wavelength range by controlling the loading of the feeding element. Importantly for our further analysis, the electric field between the inner faces of the nanorods of the feeding elements is nearly uniform, as shown by the lines of field in the bottom panel of Fig. 2. This finding will significantly simplify simulations of the nanoantenna.

The analysis of resonances denoted by B–B' (see the top panel of Fig. 2) does not reveal a significant change in the resonance wavelengths because the electric field is mainly concentrated around the directors of the nanoantenna and does not penetrate into the semiconductor,
Fig. 2. (Top) Far-field power spectra of the nanoantenna in the maximum emission direction as a function of the wavelength for different free carrier densities from 0 cm$^{-3}$ to 3·10$^{21}$ cm$^{-3}$ (from bottom curve and up). Red dashed line indicates the operating wavelength of a Yagi-Uda nanoantenna with the same dimensions but equipped with an all-metal feeding element. (Bottom) Stationary $|E|$ electric field distributions in the near-field zone of the nanoantenna corresponding to the resonance peaks denoted by the capital letters in the top panel.
as shown in the bottom panel of Fig. 2.

The C–C' resonances are more sensitive to a variation of the conductivity of the nano-disk due to the fact that at 0 cm$^{-3}$ the electric field mainly concentrates around the reflector but spreads over both the reflector and the feeding element at 3 · 10$^{21}$ cm$^{-3}$. The wavelength of C–C' resonances is blue-shifted towards the operating wavelength of an all-metal Yagi-Uda with the same geometry (red dashed line in the top panel of Fig. 2).

Since both B–B' and C–C' resonances the nanoantenna do not exhibit a correct Yagi-Uda behavior manifesting itself by a pronounced resonance of the feeding element [14], in what follows we focus ourselves on A–A' resonances only.

It is worth noting a highly desirable option of the nanoantenna excitation with a broadband point-like emitter (e.g. a fluorescent molecule) placed near one of the edges of the feeding element [16, 38]. It allows a realization of a pump-probe operation scheme, where a pump laser is used to control the coupling of the emitter to the nanoantenna at different wavelengths. Moreover, according to the principle of reciprocity the far-field characteristics of the nanoantennas in the emission regime are similar to those in the reception one [2], and, therefore, the nanoantenna can be employed as a tunable nano-receiver.

In active semiconductor nanophotonic devices, such as e.g. all-optical switches based on photonic crystal nano-cavities (see, e.g., [39]) and semiconductor antennas for THz radiation [40, 41], one usually needs free carrier densities of up to 10$^{19}$ cm$^{-3}$. As we can see in Fig. 2, in order to tune the response of the Yagi-Uda nanoantenna by ≈200 nm one needs to increase the free carrier density by two orders of magnitude as compared with that for the aforementioned nanophotonic devices. Hereafter, we demonstrate that this increase can be achieved at experimentally attainable optical intensities owing to a local field enhancement in the nano-disk loading of the feeding element.

For our further analysis, we consider that the free carrier density $N$ in the semiconductor obeys the rate equation [42]

$$
\frac{\partial N(t)}{\partial t} = -\frac{N(t)}{\tau_c} + \frac{c^2E_0^2n_0^2\beta_{\text{TPA}}}{8\hbar \omega_0} |E(t)|^4,
$$

(2)

where $\tau_c$ is the free carrier lifetime, $E(t)$ is the amplitude of the electric field, $\omega_0$ is the angular frequency of the excitation plane wave and $\beta_{\text{TPA}}$ is the two-photon absorption coefficient. We take $\tau_c = 1$ ns and $\beta_{\text{TPA}} = 120$ cm/GW [20]. Owing to the uniformity of the electric field in the nano-disk loading (see Fig. 2) in the simulations it is safe to assume that the free carrier distribution in the nano-disk is also uniform. It makes it possible to find a self-consistent solution to the nonlinear problem of the free carrier dynamics in the semiconductor using to the following numerical procedure.

First, from the steady-state rate equation we find values of $|E|$ for $N = 0 \ldots 3 \cdot 10^{21}$ cm$^{-3}$. Secondly, we use CST Studio where we fix the wavelength and the amplitude of the incident plane wave, which is a constant in all numerical experiments, and carry out simulations in order to find steady-state values of the electric field $E_d$ in the nano-disk. Then, we calculate the ratio between the electric field amplitude of the incident wave and the electric field induced by this wave in the nano-disk as $\alpha = \frac{|E|}{|E_d|}$. Finally, using the relation $E_{\text{inc}} = \alpha E_0$ we derive the real amplitudes of the plane wave that should be applied to the feeding element in order to induce the free carrier densities of up to $3 \cdot 10^{21}$ cm$^{-3}$. We have neglected here and in the following the possible nonlinear effects in metal, which are considered negligible compared to the nonlinearities in a-Si. It is also worth noting that this approach automatically takes into consideration an energy shift between near- and far-field zone peak powers [37, 43, 44].

Figure 3(a) shows the steady-state dependencies of the free carrier concentration on the optical intensity obtained using the suggested numerical procedure. In our analysis, we limit our-
Fig. 3. (a) Free carrier density in the nano-disk loading of the feeding element as a function of the optical intensity at different operating wavelengths. (b) Absolute value of the electric field in the nano-disk loading as a function of the free carrier density at different operating wavelengths.

selves to considering the spectral range between 0.95 μm and 1.05 μm, where we achieve a gradual spectral tuning by illuminating the feeding element with a laser beam (Fig. 2). The resulting dependencies display a clear signature of optical bistability [35]: for the same optical intensity applied to the nanoantenna the free carrier density in the semiconductor nano-disk exhibits two different steady states.

In order to investigate the origin of the bistable behavior, we study the near-field distribution in the gap of the feeding element. Recent studies have shown that using plasmonic dipole nanoantennas similar to our isolated feeding element, the electric field can be localized in the gap leading to a field enhancement of up to two orders of magnitude at the resonance frequency [45,46]. Figure 3(b) shows absolute values of the electric field in the nano-disk loading as a function of the free carrier density. We observe that the enhancement of the local field in the nano-disk contributes to the generation of additional free carriers and therefore leads to the formation of S-shaped curves typical of bistable systems. The maximum field enhancement takes place at the shortest of the considered operating wavelengths and gradually decreases with an increase in the wavelength. Consequently, a pronounced bistable curve is observed at the shortest wavelength and a weak bistable response corresponds to the longest one. Finally, since the field enhancement magnitude depends on the gap size, we note that the bistable curves can be tuned to a desired shape by varying the nano-disk size, thereby providing additional design flexibility.

It is worth mentioning here that we also investigated the impact of the background material on the relation between the free carrier density and the optical intensity. We found that the presence of a background does not significantly change the performance of the nanoantenna apart from red-shifting its operating wavelengths. Furthermore, the feeding element of the nanoantenna supports multiple resonances that leads to the formation of multiple steady states.

In order to gain more insight into the far-field characteristics of the nanoantenna, in Figs. 4(a)-4(e) we plot its far-field power angular diagrams calculated for different operating wavelengths. It is important for the spectral tuning that in all regimes the nanoantenna performs as an unidirectional emitter with a high front-to-back ratio and nearly constant beam-width of ≈ 80°. Moreover, by plotting the power emitted by the nanoantenna in the maximum emission direction as a function of the optical intensity [see Figs. 4(f)-4(j)], we observe the formation of...
Fig. 4. (a-e) Far-field power angular diagram of the nanoantenna in the E-plane (solid curves) and H-plane (dashed curves) at operating wavelengths (free carrier densities) of 0.95 μm (1.9 · 10^21 cm⁻³), 0.975 μm (1.5 · 10^21 cm⁻³), 1 μm (1.2 · 10^21 cm⁻³), 1.025 μm (0.8 · 10^21 cm⁻³) and 1.05 μm (0.55 · 10^21 cm⁻³). A dB scale is used to emphasize the difference in the backward lobes. (f-j) Power emitted by the nanoantenna in the maximum emission direction as a function of the optical intensity.
closed bistability loops at different operating wavelengths.

Closed loops were observed earlier in photonic systems exhibiting nonlinear Fano-Feshbach resonances resulting from the interaction between two Fano resonances located very close to each other [47]. They may have appealing applications in realizing ultra-fast all-optical switching devices at the nanoscale since the nanoantenna exhibits two different stable states for the same applied optical intensity. One relevant aspect to underline here consists in the dependence of the total hysteresis area on the operating wavelength. For certain operating wavelength the hysteresis loop may not appear, as shown in Fig. 4(j) for 1.05 μm (green curve). Such steep properties of the nonlinear response suggest the use of the Yagi-Uda architecture shown in Fig. 1 as a nonlinear optical device operating as a logical cell, an optical limiter or a signal amplitude modulator [35], also exhibiting emission properties not attainable with dipole plasmonic nanoantennas [29,48,49].

Finally, we calculate the optical intensity that maintains the nanoantenna in the appropriate operating regime. By fixing the operating wavelength at 1.05 μm and choosing a bias point in the steep part of the corresponding curve in Fig. 4(j), for the excitation with a 25-ps-long pump laser beam focused to a 1 micron squared spot, we obtain the trigger energy of ≈ 1 pJ. Bistability-based operation of the nanoantenna at shorter wavelengths would require higher pump energies of up to ≈ 5 pJ. These values are achievable in practice and are consistent with the requirements for the ideal bistable optical device [35].

4. Conclusions

We have suggested a simple way to tune dynamically a plasmonic Yagi-Uda nanoantenna and emit light in a wide spectral range. This capability is hardly achievable with conventionally designed Yagi-Uda nanoantennas whose performance is strictly optimized to just a few percent around the design frequency, and it cannot be extended significantly without a penalty. We have shown the capability of the optical Yagi-Uda nanoantennas to perform as a bistable optical device offering new degrees of freedom in controlling the far-field emission. As such, Yagi-Uda nanoantennas can be used for ultra-fast switching, mixing, frequency conversion, modulation and other kinds of all-optical light control and manipulation at the nanoscale. We have shown that the optical energy required to switch the nanoantenna to an unstable state is achievable in experiments.

Acknowledgments

This work was supported by the Australian Research Council. The authors confirm many valuable discussions with their colleagues from the Nonlinear Physics Centre and Metamaterial Meeting Group at the Australian National University.