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Review of Nanoantennas Application

Abstract. *Currently, nanoantennas represent significant potential for the future, and the scientific community is putting a lot of effort into developing these devices. Many publications deal with different types such as plasmonic, dielectric, or hybrid, and structures of nanoantennas such as dipole, Yagi-Uda, and others; therefore, the idea arose to create an article summarizing the possibilities of using these devices in the last five years. The paper focuses on a brief description of currently investigated types of antennas, especially in the scientific field, and lists the most common applications of nanoantennas.*

Streszczenie*. Obecnie nanoanteny mają znaczny potencjał na przyszłość, a społeczność naukowa wkłada wiele wysiłku w rozwój tych urządzeń. Wiele publikacji dotyczy różnych typów, takich jak plazmoniczne, dielektryczne lub hybrydowe, oraz struktur nanoanten, takich jak dipol, Yagi-Uda i inne; zrodził się więc pomysł stworzenia artykułu podsumowującego możliwości wykorzystania tych urządzeń w ciągu ostatnich pięciu lat. W artykule skupiono się na zwięzłej charakterystyce obecnie badanych rodzajów anten, zwłaszcza w obszarze naukowym, oraz wymieniono najczęstsze zastosowania anten nanoanteny.* (***Przegląd zastosowań nanoanten***)

Keywords: Nanoantenna, application, communication, materials, nanotechnology
Słowa kluczowe： nanoantenny, zastosowanie nanoanten

Introduction

Nowadays, antennas are essential devices of wireless information transmission technologies, along with sources of electromagnetic waves and their receivers. In radio engineering, antennas convert electric and magnetic currents to radio waves and conversely. [1] The requirement for miniaturization leads to a demand for adjusting the dimensions of antennas up to the order of nanometers. However, this led to difficulties because the nano-antennas could not function in the same way as conventional antennas - other frequencies. Nanoantennas work mainly in the order of THz, which offers new possibilities in communication systems because higher frequencies ensure higher speeds [2, 3, 4, 5]. In other words, terabits per second can be transmitted in this band. Another advantage lies in the size and the possibility of implementation in small devices, which finds application, especially in biomedical applications [6, 7, 8].

Due to sizes nanoantennas are quite young devices, so has no long history. In 1973 Robert L. Bailey and James C. Fletcher received a patent for an electromagnetic wave converter. Their patented device was very close to modern nanoantenna devices. In 1984 Alvin M. Marks got patent for a device, that used sub-micron antennas for the direct conversion of light into the electricity. [9].

The nanoantenna is made by three parts - the ground plane, the optical resonance cavity and the antenna. Antenna absorbs the electromagnetic wave, ground plane is reflecting the light back towards the antenna and the optical resonance cavity bends and concentrates the light back towards the antenna using ground plane. [1].

This review is divided into four sections. The first section describes the types of nanoantennas and their comparison, followed by a section outlining the implementation of nanoantennas. The third section contains the applications of nanoantennas, including a summary table showing an example of the application and the relevant publication. The contribution of the paper is described in conclusion.

Types of nanoantennas

There are several ways to divide an optical nanoantenna, such as structure (Yagi-Uda, dipole), application (medical devices), or technology. The last-mentioned division was chosen for this article, which divides antennas into plasmonic (metallic), dielectric or metal-dielectric nanoantennas.

0.1 Plasmonic nanoantennas

Plasmonics is a rapidly growing field at the nexus of photonics, electronics, and nanotechnology. Plasmonic nanostructures have opened up extraordinary ways to guide and lo-calize electromagnetic fields at physical dimensions smaller than the wavelength of light. [11, 12] Plasmonic nanoantennas are based on the interaction of a plasmonic effect called localized surface plasmon resonances with metal nanoparticles. The efficiency of the antenna is mainly affected by the material from which it is made. Today, the most common materials are precious metals such as gold [13, 14, 15], silver [16, 17, 18], and aluminum [19, 20, 21]. However, composite semiconductor structures and heavily doped semiconductors are also used. The choice of material affects the properties of the antenna, especially in the visible spectrum. The limit is insufficient performance control, which can be affected by changing the shape and size of the nanoparticle.

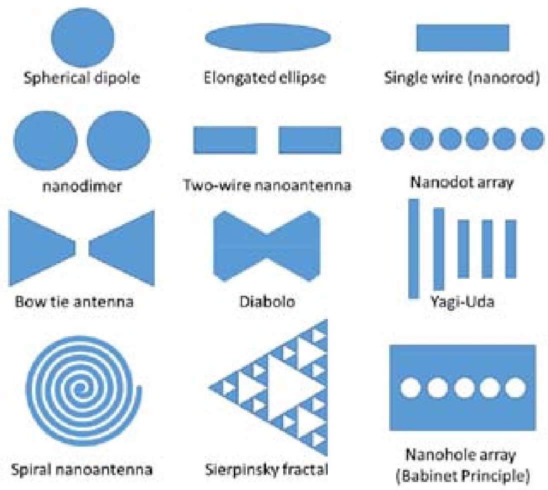

Fig. 1. Types of nanoantennas according to their shape. [10]

0.2 Dielectric nanoantennas

Unlike other nanoantennas, dielectrics prefer transparent materials such as silicon or germanium, which provide good optical properties and eliminate light scattering. [22] Antennas are characterized by their optical properties with a high refractive index. The advantages of dielectric nanoantennas are low scattering losses and amplification of both near-field components. Antennas also produce low heat, making them suitable for constant temperature applications. [23] The publication [23] proposes to divide antennas into three categories according to the number of elements, namely single-element [24, 25], two-element [26], or more elements [27].

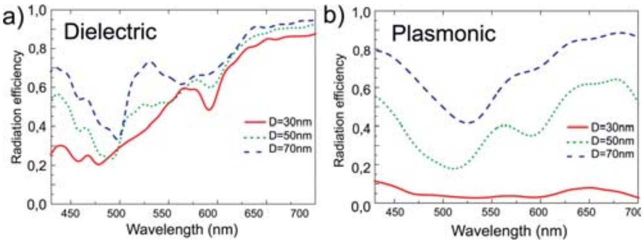

Fig. 2. Comparison of plasmonic and dielectric Yagi-Uda nanoantennasradiation efficiency. [30]

0.3 Metal-dielectric nanoantennas

Metal-dielectric nanoantennas offer a compromise of both mentioned types, i.e., a significant Purcell factor and high scattering directionality, and low scattering losses, which was experimentally confirmed by the publication [28]. Thanks to the dielectric material, the antenna has a non-resonant character. However, achieving these properties is difficult due to their combined nature. Dielectric materials complicate the achievement of the desired Purcell factor, which characterizes plasmonic antennas, and the heart of the metal elements causes loss problems. [29]

Fabrication of nanoantennas

Huge success in the fabrication of nanoscale elements allows bringing to optics, leading to the development of optical nanoantennas. One of the first fabricated optical nanoantenna was made of metallic nanorods in the classical analog of the Yagi-Uda antenna design. [30].

Nanoantennas fabrication has also been studied by Kumar, Tanwar, and Sharma; they wanted to solve the problem with nanoantenna fabrication by using gold (Au) and silver (Ag), which have skin effects at a higher frequency. Currently, material selection in nanoantenna fabrication is a complex problem because their base is gold (Au) and silver (Ag), which have skin effects at a higher frequency; however, it affects the efficiency of the nanoantenna. To eliminate this disadvantage, they decided to switch the materials on graphene and carbon nanotube because they do not affect at a higher frequency. [1].
The fact that at optical frequencies, conductivity is lower and polarization and displacement effects play a significant role in the fabrication was introduced by Alu and Engheta. [51] Another study which deals with fabrication nanoantennas is by Franceschini, Donelli, and Massa. They discovered that nanoantennas used at lower frequencies could not be directly transposed to optical frequencies because conductive materials behave differently (their permittivity could have a negative value). [52].

There are several ways to prepare samples for the production of nanoantennas [53, 54, 55, 56]; however, the most common method is lithography. The fabrication consists of two steps: selecting a suitable material and the processing process. The substrate is chosen concerning the type of nanoantenna, i.e., plasmonic [11], dielectric [30] or other. The most common substrates are silicon [57, 58] or glassbased materials [59] or a compromise in Fused quartz [60]. Silicon substrates have low resistance losses; nevertheless, they are opaque in the visible spectrum, so they can only be used for reflection applications. Another limit is the high refractive index, which causes resonant waves in the infrared range. In contrast, glass substrates have a lower refractive index and better light transmission. The limit of glass elements is the implementation in semiconductor technology, so Fused quartz is preferred, responding better to temperature changes. This material is characteristic of optical systems because it has excellent transparent properties across the visible spectrum. Other compounds with quartz, which achieves good electrical, optical and thermal properties, can be an alternative; however, the transmittance in the UV spectrum is impaired due to impurities in the production process.

Lithography is the process of applying a nanolayer of any shape to the surface of a substrate—several types, such as electron, optical, or nanoimprint lithography. The most used method is electron lithography [61], which modifies the resistor using an electron beam, leading to the dissolution of the exposed or unexposed part of the resistor. A metal layer is applied to the treated sample, removed from the resistor, or left on the substrate by lift-off [62]. This process is performed using electron microscopes or lithographic systems. Optical lithography [63] works on the principle of irradiating the photoresistor through a partially transparent photomask. The limit of the method is the produced structures, which are dependent on the wavelength. Another popular technique is nanoimprint lithography [64], which works on the principle of deformation of a polymeric resistance film using a stamp made of hard material produced by the electron method.

Application of nanoantennas

Nanoantennas have application in various branches, such as medicine [65], photovoltaics [66], spectroscopy [67], microscopy [68] or photonics [69]. Some of them are already using nanoantennas like spectroscopy; however, in medicine is excepted to start using them in the near future. Another fields (photovoltaics and photonics) are still in phrase of experimental testing with nanoantennas. [9] In medicine application of nanoantenna could be used for diagnostics and treatment of malignant tumors. Radiation causes heating of nanoparticles, that transfer heat to the cancer cells and destroys them. [9

Table 1 on the following pages shows the overview of different types of nanoathennas.

Table 1. The overview of nanoantennas types and applications.

Ref	Authors	Year	Type of nanoantenna	Problem solved
[31]	W. Rieger, J. J. Heremans, H. Ruan, Y. Kang, and R. Claus	2018	Nanolithographic Yagi-Uda	Direct electrical measurement of nanoantenna array response
[32]	Abhishek Pahuja Manoj Singh Parihar, V. Dinesh Kumar	2020	Yagi–Uda	Modification of conventional anti-reflection coating for improve performance of solar cells
[33]	Waleed Tariq Sethi,Olivier De Sagazan,Mohamed Himdi,Hamsakutty Vettikalladi and Saleh A. Alshebeili	2021	Yagi–Uda	The nanoantennas were designed to operate and respond on a center wavelength of 1550 nm

[34]	Nitin Gupta and Anuj Dhawan	2021	Yagi–Uda, Bowtie	Design of combination of Yagi-Uda and Bowtie nanoantenna, experiments for wavelength 785 nm and 1500 nm
[35]	Fatma E. Helmy, Mohamed Hussein, Mohamed Farhat O. Hameed, Ahmed Shaker, M. El-Adawy, S.S.A. Obayya	2019	Yagi–Uda	Analysis of shapes using particle swarm optimization algorithm to achieve high directivity at a wavelength of 500 nm
[36]	Victor Dmitriev, Karlo Q. da Costa	2021	Yagi–Uda	Optimization of the radiation and absorption characteristics of modified Yagi-Uda nanoantenna arrays
[37]	Jutika Devi, Pranayee Datta	2018	Yagi–Uda	Designed antenna is is achieved with only one reflector and one directon, it is ultra-compact, cost-effective and simple in the structure.
[38]	Jinfa Ho, Yuan Hsing Fu, Zhaogang Dong, Ramón Paniagua-Dominguez, Eleen H. H. Koay, Ye Feng Yu, Vytautas Valuckas, Arseniy I. Kuznetsov, and Joel K. W. Yang	2018	Metal–Dielectric Yagi–Uda	Desing of compact hybrid metal–dielectric nanoantenna that is based by Yagi-Uda design.
[39]	Kan Yao, Yuebing Zheng	2021	Spherical dielectric	Suggestion of new approach to controlling chiral dipolar emission
[40]	RamonPaniagua-Dominguez, Boris Luk'yanchuk, Arseniy I.Kuznetsova	2020	Isolated dielectric	Tailor the scattering characteristics of the nanoantennas
[41]	C. R. Simovski, M. S. M. Mollaei, and P. M. Voroshilov	2020	Plasmonic nanoantennas	With designed nanoantennas can be achieved nanolaser regime.
[42]	Na Li, Zhichao Xu, Jin Zhang and Fanji Jin	2020	Spiral	New design of spiral nanoantenna for solar energy harvesting with wavelength range from 400 to 1600 nm.
[43]	Yong Wang, Yonghua Lu, and Pei Wang	2018	Dielectric nano-dimer	Comprehensive analysis of the far-field scattering of dielectric nanodimer antennas excited precisely by a Gaussian beam.
[44]	Nyha M.Hameeda, Mohammed A. Al Lethaweab	2020	Diabolo	Designed gold diabolo antenna shows a higher magnetic field enhancement increasing with geometric changes, compared to that of the electric field.
[45]	Lisa Seitl, Florian Laible, Simon Dickreuter, Dominik A Gollmer, Dieter P Kern, and Monika Fleischer	2019	Plasmonic Sierpinski fractal	Fabrication method based on electron beam lithography and focused helium ion beam.
[46]	Junyeob Song and Wei Zhou	2018	Nanohole array	Using Au nanohole arrays as deposition masks to fabricate arrays of multi-layered composite nanoantennas.
[47]	Jun Kim,Naseem Abbas, Seongmin Lee, Jeongwoo Yeom, Md Ali Asgar, Mohsin Ali Badshah, Xun Lu, Young Kyu Kim, Seok-Min Kim	2021	Nanodot array	Simple and cost-effective method is proposed here for a plasmonic nanoantenna array for the fabrication of metal-enhanced fluorescence.

Ref	**Authors**	**Year**	**Type of nanoantenna**	**Problem solved**
[48]	Xiaolu Zhuo, Hang Kuen Yip, Qifeng Ruan, Tiankai Zhang, Xingzhong Zhu, Jianfang Wang, Hai-Qing Lin, Jian-Bin Xu, and Zhi Yang	2018	Nanorod	Design of broadside Nanoantennas Made of Single Silver Nanorods with comprehensive experiments.
[49]	Sumitra Dey, Deb Chatterjee, Edward J. Garboczi, Ahmed M. Hassan	2019	Two-wire	Optimization method that can be adapted easily for many other nanoantenna applications, facilitating the development of improved nanostructures.
[50]	Seyyed Mohammad Mehdi Moshiri and Najmeh Nozhat	2021	Dipole	Design of an optical smart multibeam cross dipole nano-antenna made by graphen with wavelenght 1550 nm.

Conclusion

The paper is designed to review the state and development of nanoantennas, including their application possibilities. The report briefly summarizes the beginnings of nanoantennas and production methods, including a description of the advanta es and disadvantages. The crucial content part is devoted to applications in recent years and the contribution of some publications in this area.

The branch of nanoantennas is relatively new, perspective, and dynamically growing. The most popular type of researcher is the dielectric Yagi-Uda designed for wavelengths from 500 to 1500 nm, i.e., for visible to IR radiation. According to available data, plasmonic nanoantennas based on silver and gold are the most popular today; however, hybrid antennas are gaining prominence, eliminating some of the shortcomings of plasmonic types regarding optical losses. An exciting trend is the development of plasmonic antennas based on aluminum or semiconductors. The application of nanoantennas has a broad spectrum, mainly are used in medicine, photovoltaics, spectroscopy, microscopy, and photonics. The article aims to briefly describe the current use of nanoantennas and present current trends in the field.

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