Geometry Optimization of Broadband and Efficient Plasmonic Modulator Antennas

Hande Ibili\textsuperscript{1}, Student Member, IEEE, Arif Can Gungor\textsuperscript{1}, Student Member, IEEE, Jasmin Smajic\textsuperscript{1}, Senior Member, IEEE, and Juerg Leuthold\textsuperscript{1}, Fellow, IEEE

\textsuperscript{1}Institute of Electromagnetic Fields (IEF), ETH Zurich, Switzerland, \{hibili, arifg, smajicj, leuthold\}@ethz.ch

Plasmonic modulator antennas with high field enhancement values are essential to detect weak fields at high speeds in future communication systems. Consequently, such antennas with high field enhancement values at frequencies reaching up to 500 GHz are rising interest in the research. These antenna systems enable direct mapping of electromagnetic waves onto the optical signals; thereby, eliminate the radio frequency (RF) losses that are introduced by the conventional RF to optical conversion systems. The high field enhancement values over a broad frequency bandwidth at millimeter-wave frequencies enable efficient, robust, and accurate operation. The geometry of the antenna, as well as the dimensions of the geometric parameters, determine the field enhancement response with respect to frequency. In this work, we have optimized the geometry and design of the plasmonic modulator antenna by means of a genetic algorithm and have presented promising results.

Index Terms—Field enhancement, Genetic algorithm, Optimization, Plasmonic antenna.

I. INTRODUCTION

New generation mobile network systems offer significantly faster communication speeds and extensive data transfer. As 5G & 6G applications utilize higher frequency bands in the pursuit of broader bandwidths and higher transfer rates, photonic and plasmonic communication systems have started replacing traditional electronic counterparts. As it was shown by [1], modulation frequencies up to 500 GHz have been reached by plasmonic modulators. In [2], authors have shown successful plasmonic detection in the 300 GHz range. Both the modulators and detectors in these systems employ antennas that enables direct conversion between radio frequency (RF) and optical signals in order to provide the required bandwidth and high speeds. Therefore, advanced antennas that comply with plasmonic technology requirements emerge for future of the communication systems. Consequently, this article intends to focus on optimization of the field enhancement type antennas that can be utilized in devices that are operating plasmonic modulators and detectors.

The main objective of this paper is to present the optimization of plasmonic bow-tie antenna and their geometry to reach the highest field enhancement across a broad spectral frequency range by using a genetic algorithm.

The digest is organized as follows. Section II outlines the plasmonic modulator antenna design that will be optimized. In section III, the optimization method is presented with the numerical results, and section IV concludes the paper with remarks and future work until the time of the conference.

II. PLASMONIC MODULATOR ANTENNA DESIGN

The envisioned plasmonic modulator antenna design is depicted in Fig. 1. It consists of a millimeter-wave bow-tie antenna and a plasmonic phase modulator that is located at the slot of the antenna to fulfil the purpose of direct conversion of RF waves to optical signals [3]. The antenna is illuminated via plane-wave ($E_i$) polarized in $x$ direction and propagating in $-z$ direction. The antenna part is constructed by two antenna arms and a capacitor plate (where the generation of plasmonic phase modulation occurs) in the middle. The silicon waveguide ($E_{opt, in}$) is fed into the plasmonic phase modulator slot, where the antenna confines the electric field ($E_{slot}$). The field enhancement is calculated by $FE = E_{slot}/E_i$.

For the antenna design, the opted bow-tie geometry has six different design parameters: length of the antenna ($L_{ant}$), inner and outer widths of the antenna ($w_i$ and $w_{out}$), width of the capacitor plate ($w_{cap}$), width of the plasmonic phase modulator ($w_{PPM}$), and width of the slot ($w_{slot}$). The antenna is modelled as a perfect electric conductor (PEC). The characteristics of the plasmonic modulator antenna are determined by these design parameters, and each parameter has combined and coupled effects on the field enhancement characteristics of the antenna. Therefore, a large set of combinations should be tested and analysed to achieve the aimed field enhancement in the interested wide frequency range. To that end, we utilize an evolutionary optimization procedure for the design parameters.

III. GENETIC ALGORITHM OPTIMIZATION OF PLASMONIC MODULATOR ANTENNAS

The field enhancement response of the antenna in the interested frequency range depends on the geometric design...
parameters. The optimization of these parameters is carried out by employing an in-house developed genetic algorithm [4]. Full-wave simulations with COMSOL software are used for the electromagnetic solver part in this optimization procedure. Thereby, MATLAB Livelink is implemented to connect the electromagnetic solver with the genetic algorithm. The computation of the fitness values is performed with MATLAB using the cost function given in (1), and the goal of the optimization is to maximize the fitness value in the interested frequency range.

\[
CF = \| |FE| - FE_{ref} \|_2, \text{ where } |FE| > FE_{ref} \tag{1}
\]

where \(FE_{ref}\) is the desired minimum field enhancement value and \(FE\) is the field enhancement vector, where the value of the field enhancement is larger than the desired minimum field enhancement value. In the optimizations, a population size of 20 with 100 generations are used. The overall chromosome length is selected as 50.

As a reference, the minimum field enhancement of 2000 is set for the frequency range from 100 GHz to 300 GHz. The design parameters mentioned in the previous section are optimized except for the slot width. The slot width, \(W_{slot}\), has a large impact on the field enhancement value and a narrow slot inherently results in high field enhancement. Therefore, the slot width is fixed at 750 nm for the optimizations.

Fig. 2 shows field enhancement characteristics of the two antennas produced by the optimizer. The ‘best’ one provides peak enhancement over 4000 and maintains enhancement above 2000 for bandwidth of up to 80 GHz. Whereas the ‘worst’ one has significantly lower enhancement capabilities. The visualization of both antennas and respective geometrical values are given in Fig. 3 to verify the optimizer. Here, \(L_{ant}\) and \(w_{PPM}\) parameters mainly determine the full-wave resonance frequency, where the peak enhancement occurs. In addition, comparatively small values of \(w_{i}\) and \(w_{ant}\) lead to desired field enhancement characteristics, while having larger values instead provides wider bandwidth and gives a smoother enhancement profile. It is also observed that the \(w_{cap}\) value has a minor impact on the field enhancement response of the designed antenna.

For the ‘best’ case, the near field electric field intensity distribution on the \(xy\) plane at 150 GHz (corresponding full-wave resonance) is observed as shown in Fig. 4. The full-wave resonance behaviour of the antenna is clearly visible. The strong field confinement at the plasmonic slot is achieved.

We also note that the structure of the antenna can be transformed from bow-tie to dipole by selecting design parameters accordingly, as implied by the arrows in Fig. 1.

IV. CONCLUSION AND FUTURE WORK

In this digest, the optimization of the bow-tie plasmonic modulator antenna geometry by employing a genetic algorithm is presented. As demonstrated in the results, doubled peak field enhancement value (with respect to the reference value) with 80 GHz bandwidth is achieved. The proposed optimization introduces a sophisticated way to enable ‘best’ possible antenna designs for the aimed field enhancement response since the design parameters are dynamically coupled. The utilization of promising and efficient designs in antenna-based high-frequency and broadband field detectors is foreseen. In the full paper, intricate antenna structures will be optimized to obtain broadband and high field enhancement characteristics. The optimization procedure will be extended to cover diverse design parameters of the plasmonic modulator antennas.

REFERENCES