Terahertz Antenna Design Using Machine Learning Assisted Global Optimization Techniques

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***Abstract*—In the terahertz (THz) frequency band, high path loss necessitates designing the antenna with high-gain characteristics, making it challenging to obtain an optimal design solution. This paper investigates the feasibility of artificial intelligence (AI)-driven antenna design techniques to address the challenges, specifically the Surrogate Model- assisted Differential Evolution for Antenna Synthesis (SADEA-I) algorithm. SADEA-I has been employed for the first time (to the best of our knowledge) to optimize THz antennas. The simulation results show that SADEA-I is more effective than conventional design methodologies. Additionally, it takes only 30 hours to perform the global optimization, and it is a fully automated process and does not require any initial design.**

I. Introduction

With the growing need for high-speed, reliable, and secure wireless communication, research trends have shifted towards the high-frequency THz spectrum, particularly to the 0.1–3 THz range. Therefore, it has gained a great deal of interest in applications including THz imaging, future radars, high-data-rate mobile communications, and beyond 5G [1]. In a typical THz communication system, the transmission antenna must be low-cost, compact, and wide band. Thus, designing an antenna to meet the requirements of THz applications could be quite challenging.

A main design challenge is that the THz spectrum yields a smaller dimension structure, and the gain can be improved with an increase in the aperture. In other words, achieving a wide band characteristic with high directivity is very difficult without enlargement of the dimensions of a typical THz antenna. Therefore, to design THz antennas, more stringent features are required: a combination of high gain, ultra-wideband/multiband functionality, compact size (low profile) and conformal design. Designing an antenna incorporating all these performance metrics demands a more innovative design optimization procedure in comparison to conventional methods.

There are two kinds of conventional methods: (a) parametric study with local optimization – this method relies heavily on experience-based techniques to obtain a good initial design and could be time-consuming without any guarantee of a successful outcome [2]. (b) standard global optimization techniques used in EM simulation tools that do not require an initial design – they can be computationally expensive and require a large (sometimes unaffordable) number of EM simulations to find the optimal solution. Hence, the emergence of AI-driven antenna design optimization methods, particularly, machine learning-assisted global optimization techniques for antenna design [3]. The primary goal is to achieve a highly optimal design while significantly saving the design time and eliminating the need for an initial design.

Although AI-driven antenna design techniques have shown many successes, they have not been used for THz antennas to the best of our knowledge. Therefore, this paper investigates the feasibility of employing AI-driven design techniques, particularly, a state-of-the-art algorithm, SADEA-I [4], for the design THz antennas through a case study.

II. SADEA Algorithm

In SADEA-I, the supervised learning method is Gaussian process (GP), and it is used for the construction of surrogate models that approximate antenna performances. The surrogate modelling works harmoniously with differential evolution (DE)-based global search for a balanced exploration and exploitation of the antenna design search space. In SADEA-I, the model management method is the surrogate model-aware evolutionary search framework [5]. The flow diagram of SADEA-I is shown in Fig 1, and it works as follows: In each iteration, a surrogate model is built using available simulated candidate designs and their performances. New candidate designs are generated by search operators, and their performances predicted by the surrogate model. Using the prediction result, candidate designs with high potential are simulated and used to update the surrogate model for the next iteration. More details about SADEA-I can be found in [4]. Note that SADEA- I is the first generation of the SADEA algorithm series [6].

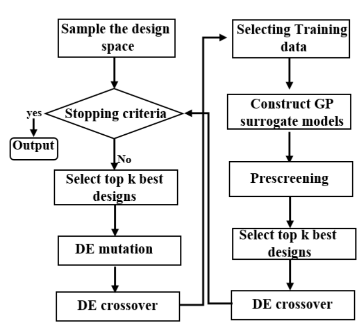

Fig. 1. SADEA-I Flow Diagram

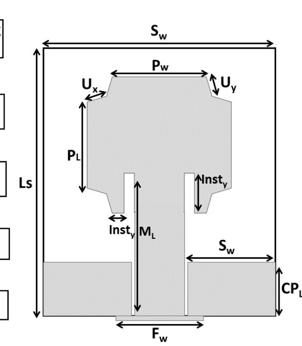

Fig. 2. Antenna Layout

III. CASE STUDY

The proposed antenna geometry consists of a truncated patch driven by a 50Ω microstrip line, two rectangular ground planes constituting a partial ground, and an inset feed mechanism. The antenna is implemented on a polyamide substrate of thickness 125μm with ε_r= 3.5 and tan(δ)= 0.0025. The results obtained by the traditional experience-driven parameter study technique is shown in Figs. 3-5. SADEA-I is then employed; the design exploration goal is to adjust the dimensions shown in Table 1 for an operational -10 dB impedance bandwidth of 0.75 to 1.4 THz. Thus, there is a single objective function and two constraints, as shown in the following expression:

$$\begin{aligned} &\text{minimize} \quad \max|S_{11}| \quad (0.75 \text{ to } 1.40 \text{ THz}) \quad \rightarrow (1) \\ &\text{subject to:} \quad \text{min total radiation efficiency} \geq 75\% \\ &\qquad\qquad\quad \text{min realized Gain} \geq 6 \text{ dBi} \end{aligned}$$

To handle the constraints, a penalty coefficient of 50 is used. All the SADEA-I parameters used the default setting [4]. The search ranges for the design parameters considered for the optimization are shown in Table I. To keep the patch, CPW ground planes and wave guide port of the THz antenna resting on the substrate in all possible cases during the optimization, the following geometric constraints are used: $(Cp_L < M_L, F_w < S_w)$. After 300 EM simulations, costing about 30 hours, SADEA-I converged to obtain the design solution reported in Table I. The simulated frequency responses of this design are shown in Figs. 3-5. From Figs. 3-5, it can be seen that the SADEA-I generated design that meets the required specifications on the radiation efficiency and realized gain over a wider -10 dB impedance bandwidth in comparison to the designed obtained using the traditional approach. The comparisons are further detailed in Table II.

TABLE I
SEARCH RANGES OF THE OPTIMAL DESIGN OBTAINED BY SADEA-I (ALL IN μm)

Variable	S_w	CP_L	P_L	P_w	M_L	U_x	F_w	$Inst_y$	$Inst_x$
Lower Bound	200	10	150	175	50	15	5	10	2
Upper Bound	500	170	290	290	200	35	11	80	40
Optimum	490	54.02	163.29	173.06	171.14	30.12	9.45	48.15	12.32

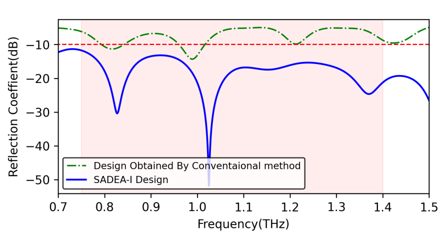

Fig. 3. $|S_{11}|$ Response

CONCLUSION

In THz antenna design, obtaining an optimal design could be challenging and time-consuming because THz antennas are highly directive with high gain. Strict design requirements and constraints on the topology in the form of geometric constraints also make the typical THz design problem complex for optimization. In this work, AI-driven antenna design method, specifically SADEA-I, is used to address the above challenges, as verified by a case study of a THz patch antenna that shows highly improved performance (in comparison to its conventional counterpart) after the SADEA-I optimization process.

TABLE II
COMPARISON PERFORMANCES

Item	**Design Obtained By Conventional method**	**Design Obtained By SADEA-I**
Maximum Reflection Coefficient $\|S11\|$ (0.75 to 1.4 THz)	-5 dB	-11 dB
Minimum Realized Gain	2 dB	6.2 dB
Minimum Total Radiation Efficiency	60 %	85 %

Note* Conventional method used here is a parametric study with local optimization, as mentioned in the previous section.

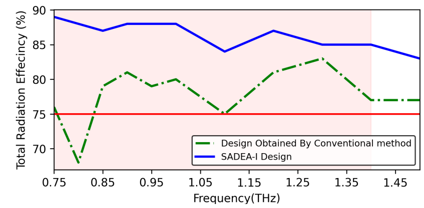

Fig. 4. Total Radiation Efficiency Response (SADEA-I)

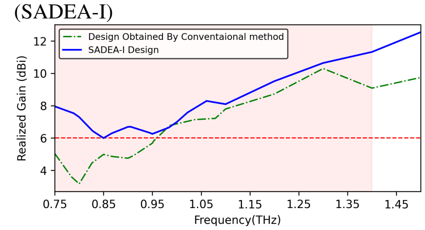

Fig. 5. Realized Gain Response (SADEA-I)

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