Design and Evaluation of MXene-Based Patch Antenna for Strain Sensing Applications: A promising Cyber Physical System Technology

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Abstract — This paper presents a novel antenna design for strain-sensing applications operating at 3.5 GHz. The proposed antenna design is based on a conventional circular patch antenna using a polyimide substrate having dielectric constant of 3.5 and thickness of 0.1 mm. The overall dimension of the antenna is 30 x 28 x 0.1 mm^3. The antenna is initially designed with various conducting materials such as Aluminium, Copper, Gold & Silver as a patch to study their effect on antenna performance. Further, MXene is deployed as the conducting patch material which shows excellent performance when compared to other conducting materials. Additionally, the study also investigates the impact of varying thicknesses of MXene on the antenna's parameters. The results reveal that increasing the thickness of MXene enhances the antenna's performance. The reflection co-efficient was found to be -25.6 dB when MXene of thickness 50 microns was used. Similarly, other antenna parameters such as VSWR, Gain, Directivity, Efficiency and Radiation characteristics are studied. The results show that MXene-coated patch antennas could be used as potential design in Cyber Physical System solutions especially for strain sensing applications.

Keywords — Circular Patch; CPS; MXene; Strain Sensing

I. Introduction

Cyber-physical systems (CPS) are a class of systems that utilize computation, networking, and physical processes to create intelligent systems[1]. CPS operate at the intersection of the physical and digital worlds, forming a feedback loop between these domains. Antennas are critical components of CPS that serve as the interface between the physical and digital worlds, allowing for wireless communication and sensing. With the growing demand for wireless communication and sensing in CPS, there is a need for advanced antenna designs that can operate in challenging environments. MXene, a two-dimensional material, has recently emerged as a promising candidate for antenna design in various applications. Several studies have highlighted the potential of MXene-based antennas in achieving high performance in terms of bandwidth, gain, and efficiency[2]. Various study on MXene based antennas have been discussed in the literature. The authors in [3] have presented an antenna for pressure and level sensing at 5.8 GHz using MXene as a patch. A 20 x 20 mm^2 patch antenna using MXene has been developed in [4] for strain sensing applications. A descriptive review on MXene that can be effectively used for various sensing application is studied in [5]. Various antenna designs have been emerging in the field of IoT based applications.

In this article, we will explore the need for antenna design in CPS and discuss the potential of MXene-based antennas in achieving high performance. The paper investigates the use of MXene as a constructive material to be used as conducting patch for sensing applications. The conventional patch antenna is studied by analysing various conducting materials as patch and the thickness of the MXene conductor is varied to analyse the betterment in the antenna performance results. The further section of the paper studies the Antenna design methodology followed by antenna performance comparison and result discussion. Finally, the paper concludes the potential advantages of MXene in the field of antenna design precisely for CPS applications..

II. Antenna Design

The initial design of the antenna involves calculation of conventional circular patch antenna for 3.5 GHz. The antenna is designed on a polyimide substrate have a dielectric permittivity of 3.5 and thickness of 0.1 mm. The simulation of the antenna is done using the Keysight Advanced Design System (ADS©) tool using the MoM computational technique. The following equation describes the radius of the patch,

$$r = \frac{0.412\,\lambda}{\sqrt{\varepsilon_r}\sqrt{1-\frac{\varepsilon_{eff}}{\varepsilon_r}}} \tag{1}$$

where,
r is the radius of the patch, ε_r is the dielectric permittivity of the substrate and λ is the wavelength at 3.5 GHz [6]. The effective dielectric constant needs to be studied because the substrate medium and air medium coming into junction to decide the overall dimensions of the antenna design. The value of effective ε_r is given by,

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\sqrt{1+\frac{12\,h}{W}} \tag{2}$$

From the calculations, it is found that the overall dimension of the antenna is designed to be 30 x 28 x 0.1 mm^3. The following Fig. 1. shows the front and back view of the proposed antenna design along with detailed dimensions.

Further, to investigate the performance of the antenna various patch materials are used. Initially the patch is defined with copper as substrate having a thickness of 35 microns and the ground plane also with copper having thickness of 35 microns. The following Fig. 2. depicts the side view of the substrate showing the patch and ground with detailed descriptions.

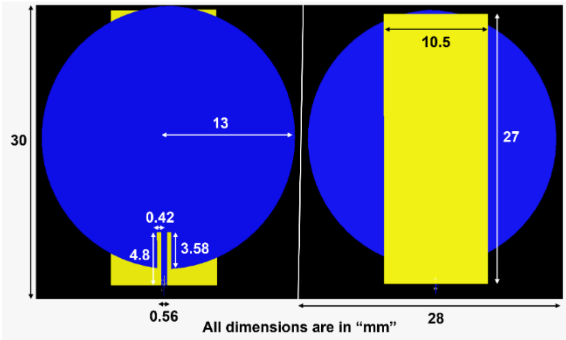

Fig. 1. Front & Back View of the proposed antenna

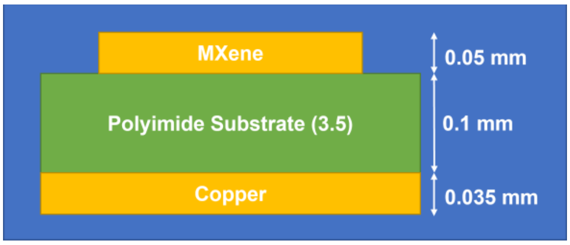

Fig. 2. Side view of the substrate

The design is further analysed by varying the patch using different conductors. To streamline the study on different conductors the ground plane is fixed to be copper having thickness of 35 microns and the patch is made of thickness 50 microns. The following Table I describes various conductors with its conductivity listed.

Table I. Materials with their conductivity values

Conducting Material	Conductivity (S/m)
Aluminium	3.72 x 107
Copper	5.8 x 107
Gold	4.1 x 107
MXene	1 x 106
Silver	6.17 x 107

III. SIMULATION RESULTS

The foremost important parameter to check the antenna performance is the reflection co-efficient which describes the amount of signal coming back to the source. It is evident that a better reflect co-efficient signifies less power is reverted nevertheless it does not provide any details on the amount of power received at the destination. The reflection co-efficient of the designed antenna is depicted in Fig. 3. which shows the comparative result of the reflection co-efficient in dB for various conduction patch.

From the figure, it is seen that MXene offers an effective reflection co-efficient of -25.6 dB at 3.5 GHz. Therefore, we see MXene to be a potential material to be used as patch. Furthermore, various thickness of the MXene is also studied to understand the performance as an antenna with respect to the thickness of deposition on the substrate. The following Fig. 4. shows the results of reflection co-efficient in dB for MXene as patch by varying its thickness between 5 microns and 100 microns.

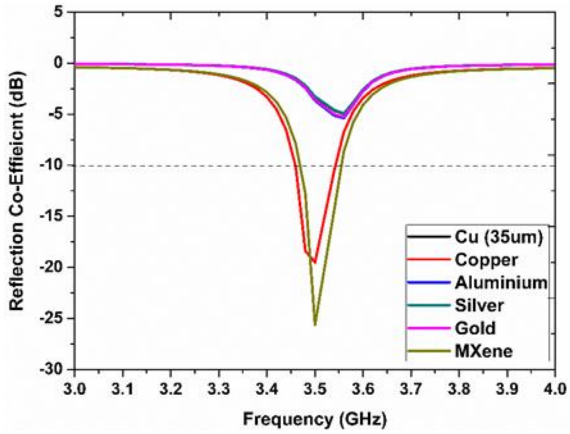

Fig. 3. Reflection Co-Efficient in dB

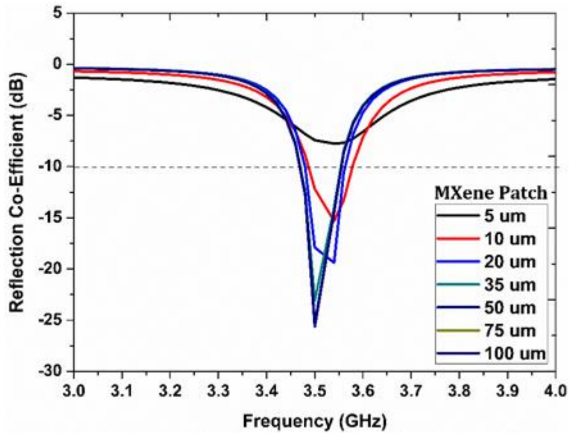

Fig. 4. Reflection Co-Efficient for varying MXene thickness

From the simulated results, it is clearly seen that MXene used as a patch with thickness of 50 microns show the highest performance at 3.5 GHz. Further antenna results describe the antenna parameters for these specifications. The following Fig. 5. describes the VSWR of the given antenna. The Voltage Standing Wave Ratio (VSWR) describes the amount of standing waves in the design. The value of VSWR should be low and close to 1. It is seen that the antenna offers VSWR of 1.43 and impedance is close to the centre of smith chart which infers considerable matching is achieved. The impedance is found to be close to 50 Ohms at 3.5 GHz.

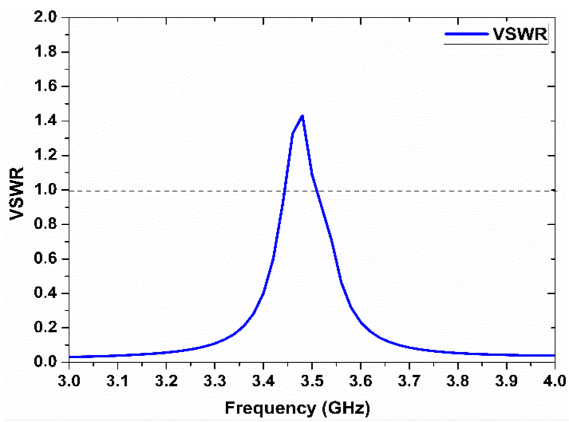

Fig. 5. VSWR of the proposed antenna

The current distribution of an antenna signifies the radiation fields of an antenna. The designed patch shows concentrated current around the edges of the patch. The maximum current is found along the centre of the patch and the defected ground structure significantly alters the current resulting in high current density. The following Fig. 6. describes the current distribution of the proposed antenna.

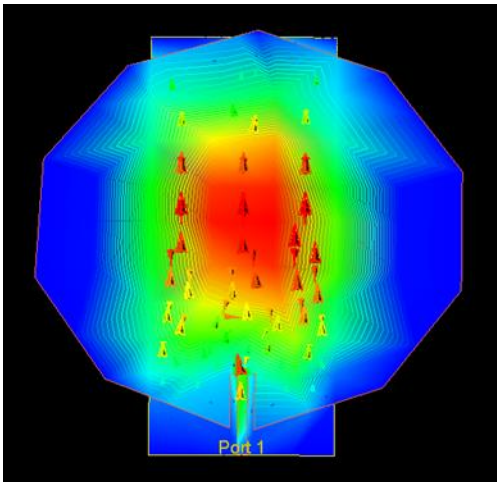

Fig. 6. Current Distribution of the proposed antenna

The radiation pattern of the designed antenna is studied in Fig. 7. It is seen that bi-directional radiation pattern is obtained in the direction of theta and an omni-directional pattern with a null close to the axis of antenna is obtained in the direction of phi. The pattern is very similar to the pattern obtained to a conventional antenna.

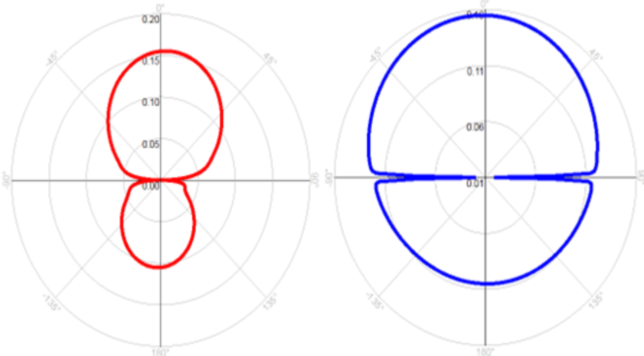

Fig. 7. E – Field Pattern (Theta & Phi)

Various other antenna parameters such as gain, directivity and efficiency of the antenna for various materials used as conduction patch are described in detail given in Table II.

TABLE II. Antenna Parameters

S. No.	**Material**	**Gain (dBi)**	**Directivity (dBi)**	**Efficiency (%)**
1	Aluminium	-3.11	3.60	21.3
2	Copper	-7.88	3.61	7.1
3	Gold	-3.02	3.60	21.7
4	Silver	-2.70	3.61	23.4
5	MXene	-7.90	3.62	7.03

The antenna design under consideration having MXene as conducting patch offers gain of -7.9 dBi, directivity of 3.62 dBi and radiation efficiency of 7.03 %. In general, an antenna designed is supposed to have high gain. But, for CPS applications, especially when using the antenna for strain sensing applications it is important that gain to be low as the near field measurements are going to highly be impacted for its study and also low gain helps in providing high sensitivity changes in the environment of study. From these simulated results, we see that MXene based patch antennas offer high standards of antenna performance compared to other conducting materials used as the patch.

IV. CONCLUSION

This paper provides an investigative study and design of a circular patch antenna for strain sensing applications. The antenna design is tested by changing various materials that can be used as a patch. From the simulated results, it is observed that MXene with thickness of 50 microns offer better antenna performance at 3.5 GHz. The overall dimension of the antenna is found to be 30 x 28 x 0.1 mm3 with polyimide substrate having dielectric constant of 3.5 and thickness of 0.1 mm. The reflection co-efficient is found to be -25.6 dB having a VSWR of 1.43. The gain and directivity of the antenna is -7.9 dBi and 3.62 dBi respectively. The radiation efficiency is 7.03 %. From the antenna performance results, it is evident that the proposed antenna can be used as a potential system for strain sensing applications.

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