Anomalous Radio Frequency Conductivity and Sheet Resistance of 2D Ti$_3$C$_2$Tx MXene

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This work was supported in part by the National Science Foundation under Grant 1816387 and Grant 2034114, and in part by the Drexel University Libraries Open Access Publishing Fund.

ABSTRACT In this paper, we demonstrate the anomalous radio frequency (RF) performance of a 2D nanomaterial, Ti$_3$C$_2$Tx MXene, by extracting conductivity and sheet resistance at both direct current (DC) and RF. Two-port microstrip transmission lines with detachable top layers, copper ground layer, and end launch connectors were fabricated. MXene transmission lines were manufactured through the deposition of layers with thicknesses of 2 $\mu$m, 1 $\mu$m, and 0.2 $\mu$m onto polyethylene terephthalate (PET) substrates. Copper transmission lines were fabricated to serve as a benchmark. Two-port $S$-parameters were measured using a network analyzer from 0.9 GHz to 1.4 GHz and Telegrapher’s equation $RLGC$ parameters (per unit length resistance $R$, inductance $L$, conductance $G$, and capacitance $C$) were extracted. The RF sheet resistance values of MXene films, as well as copper, were extracted from the $R$-values. $S$-parameters were simulated with the extracted RF sheet resistance values and a good match was found with the measured values. $S$-parameters were also simulated using the 4-point conductivity and thickness of the MXene films. The RF conductivity of the MXene coating was found to be 35,000 S/cm, higher than the DC conductivity of the material (10,000-15,000 S/cm). This work gives a guideline on designing MXene-based communication devices which are different from those fabricated with conventional metals.

INDEX TERMS Conductive 2D nanomaterial, flexible antenna, MXene, radio frequency sheet resistance, Ti$_3$C$_2$Tx, transmission line.

I. INTRODUCTION
With the explosive growth of the Internet of Things (IoT) and fifth generation (5G) mobile devices, thin and flexible radio frequency (RF) components are highly desired. MXene is a large family of two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides [1]. Among them, Ti$_3$C$_2$Tx (T$_x$ stands for the surface functional groups, =O, -OH, -F, etc.) - which is the first discovered MXene [1], has been demonstrated to have great potential for RF wireless communication and electromagnetic interference shielding, owing to its high metallic conductivity [2]–[4]. MXene-coated conductive fabrics have also been developed to be potentially used for wearable RF applications [5]. Furthermore, MXene is a hydrophilic and solution-processable conductive nanomaterial that offers excellent flexibility and can be deposited on any surface to achieve complex RF structures using many different coating techniques, including spray-coating, inkjet-printing, screen-printing, blade coating, etc., [6]–[8]. In addition, the thickness of MXene coatings can be controlled at the nanometer scale, due to the nanometer-thick MXene flakes.

In software packages such as High Frequency Structure Simulator (HFSS), CST Microwave Studio, etc., the simulations are done assuming material parameters do not vary with frequency. This creates difficulties when simulating conductive 2D MXene, as the usual assumptions of metallic bonding cannot be applied.

The electrical conductivity of MXene film consisting of stacked flakes is anisotropic. Previous works [2], [9] have shown that MXenes have superior conductivity at RF compared to DC. However, both works compared measured and simulated $S$-parameters of two-port MXene transmission lines, and extracted the RF conductivity from regression. In this paper, besides directly extracting RF conductivity,
we prove the DC-RF dual nature of MXene by comparing the sheet resistance values at both DC and RF. While DC sheet resistance of conductive films can be measured with a four-point probe device, there is no direct method of measuring RF sheet resistance. We applied a recently developed technique [10]–[12] for RF sheet resistance extraction from transmission line measurements that was initially developed for conductive fabrics.

The anomalous RF conductivity and sheet resistance of MXene takes us one step closer to understanding this novel conductive 2D nanomaterial. It is important to develop a new model for addressing the currents through MXene flakes in different layers. There are various types of MXenes depending on the chemical structures. The inter-layer bonding between MXene layers is very weak. Hence, it is possible to modify the inter-layer space through intercalation (insertion of molecules into layered materials) [13]. This type of application can increase the electromagnetic (EM) shielding capabilities of MXene [14]. MXenes have been used to develop sensors for neural activity monitoring [15], alkali detection [16], etc. Those sensors work based upon the change in the transistor channel characteristics and current in the presence of the molecules being sensed. Similarly, it is possible to build sensors by exploiting the anomalous RF conductivity along with nano-engineering in the inter-layer spaces in MXene.

This paper is organized as follows: section II shows the preparation of MXene samples, section III demonstrates radio frequency sheet resistance extraction of MXene at 936 MHz, section IV discusses the simulation of transmission lines using the extracted sheet resistance values and DC conductivity-thickness values. Section V presents the results that verify the extraction and sheds light on a possible mechanism for anomalous conductivity of MXene.

## II. MATERIAL PREPARATION

Ti$_3$C$_2$T$_x$ MXene was synthesized by selectively etching Al layers from Ti$_3$AlC$_2$ [17]. Typically, 1 g of Ti$_3$AlC$_2$ powder (−325 mesh) was gradually added to a mixed solution of HF (2 mL; 29 M), HCl (12 mL; 12 M), and deionized (DI) water (6 mL), and then was stirred for 24 h at room temperature. After that, the solution was centrifuged with DI water at 3500 rpm for 2 min. The washing process was repeated until pH > 6. The obtained multilayered MXene was delaminated with LiCl. The MXene clay was mixed with 1 g of LiCl and 50 mL of DI water and stirred for 4 h. The mixture was washed using a centrifuge until the sediment was swelled. The swelled sediment was dispersed in water and shook for 15 min. After that, the supernatant with a few-layered MXene was obtained after centrifugation at 7,500 rpm for 3 min. Fig. 1a shows the SEM (Zeiss Supra 50VP, Germany) image of as-synthesized MXene flake with a lateral size of > 3 µm.

MXene transmission lines were fabricated using the spray-coating method. The as-synthesized MXene colloidal solution (10 mg/mL) was manually sprayed onto a plasma-treated polyethylene terephthalate (PET; 100 µm thick) surface. After that, the sprayed samples were dried at 70°C for 12 h in a vacuum. The smooth purple surface of the MXene transmission line was observed using a 3D laser scanning confocal microscopy (Keyence, VK-X1000, Japan), as shown in Fig. 1b. The cross-section SEM image of MXene coating shows the stacked MXene flakes with good alignment (Fig. 1c), which is different from conventional metal coatings.

## III. EXTRACTION OF RF SHEET RESISTANCE

### A. TRANSMISSION LINE FABRICATION

A 41 mm × 20 mm × 1.6 mm single-sided FR4 board (Fig. 2) was prepared using a milling machine. Since the PET substrate cannot endure direct soldering, push-type end-launch SMA connectors were used to connect the transmission line to the network analyzer. MXene/copper strips were placed on the bare side of the board while the copper-clad side worked as the ground plane. The top layers (MXene/copper) of the transmission lines were 41 mm × 3 mm in size. The top layer was attached to the substrate using double-sided tape. The top layers were tapered at both ends to prevent accidental contact with the SMA ground plane.
B. RF SHEET RESISTANCE EXTRACTION

The extraction of RF sheet resistance of the different MXene samples (2 μm, 1 μm, and 0.2 μm thickness) was done at 936 MHz.

The $S$-parameters ($S_{ij}$; $i,j = 1, 2$) of these two-port transmission lines were measured with a vector network analyzer from 0.9-1.4 GHz. The true $S$-parameters of the device under test (DUT) were derived by separating the contribution of the connectors using the following equation,

$$[S_{\text{Measured}}] = \begin{bmatrix} e^{-j\theta} & 0 \\ 0 & e^{-j\theta} \end{bmatrix} \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} e^{-j\theta} & 0 \\ 0 & e^{-j\theta} \end{bmatrix}$$

(1)

where $\theta = \beta l_c$, $\beta$ is the propagation phase constant, and $l_c$ is the length of each connector. $ABCD$ parameters were extracted from the measurement-plane-corrected $S$-parameters,

$$A = \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{2S_{21}}$$

(2a)

$$B = Z_o \frac{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}}$$

(2b)

$$C = \frac{1}{Z_o} \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2S_{21}}$$

(2c)

$$D = \frac{1}{Z_o} \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}{2S_{21}}$$

(2d)

where $Z_o$ is the normalizing impedance (50 Ω). The extracted $ABCD$ parameters were used to extract the characteristic impedance ($Z_c$) and propagation constant ($\gamma = \alpha + j\beta$) of the transmission line,

$$Z_c = \sqrt{B/C} \quad \gamma = \frac{1}{l} \cosh^{-1}(A)$$

(3)

where $l$ is the length (41 mm) of the transmission line. Since the extraction of $RLGC$ parameters is an ill-posed mathematical problem [18], the direct extraction gives rise to unexpected values of the $R$ and $G$ parameters. We accepted $\gamma$ and reconstructed $Z_c$ by optimization (matching reconstructed $S$-parameters with measured values). The per unit length distributed $RLGC$ parameters,

$$R = \text{Re}(\gamma Z_c); \quad L = \text{Im}(\gamma Z_c)/\omega \quad (4a)$$

$$G = \text{Re}(\gamma/Z_c); \quad C = \text{Im}(\gamma/Z_c)/\omega \quad (4b)$$

where $\omega = 2\pi f$ ($f$ is frequency in Hz) is the angular frequency. Extracted $RLGC$ parameters are plotted in Fig. 3. To validate the extracted parameters, propagation constant (Fig. 4), characteristic impedance (Fig. 5), and $S$-parameters (Fig. 6) were reconstructed from the $RLGC$ parameters [18], [19],

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}; \quad Z_c = \frac{R + j\omega L}{G + j\omega C} \quad (5a)$$

$$[S_{\text{Rec}}] = \frac{1}{D_s} \left[ (Z_c^2 - Z_o^2) \sinh \gamma l \right]$$

$$\gamma = \frac{1}{Z_o} \left[ \frac{2Z_c Z_o}{(Z_c^2 - Z_o^2) \sinh \gamma l} \right] \quad (5b)$$

where $D_s = 2Z_c Z_o \cosh \gamma l + (Z_c^2 + Z_o^2) \sinh \gamma l$. We assumed the transmission line was symmetric and reciprocal ($S_{11} = S_{22}$ and $S_{12} = S_{21}$). The extracted R-parameter (Eq. 4b) was then used to calculate the sheet resistance at our frequency of interest (936 MHz). Fig. 7 shows the extracted $R$-parameters of the three transmission line groups.

In our previous work [12], we showed that the copper-clad ground layer resistance is negligibly small compared to the top layer resistance. This is a generally valid approximation as long as the top layer material has larger resistivity (or smaller conductivity) compared to copper. In Fig. 8, HFSS simulation results show that the radiation efficiency of the transmission line is less than 2% for a broad range of sheet resistance values at 936 MHz. In other words, the radiation resistance of the transmission line is significantly smaller compared to the total RF resistance. Hence, we make the approximations that $R_{\text{MXene}} \approx R_{\text{total}}$ and $R_{\text{rad}} \approx 0$.

The RF sheet resistance ($R_s$, Ω/sq) of MXene is,

$$R_s = \left( \frac{w}{l} \right) R_{\text{MXene}}$$

(6)

where $w$ (3 mm), $l$ (41 mm), and $R_{\text{MXene}}$ are the top-layer width, transmission line length, and the RF resistance of the top-layer MXene film, respectively. Extracted RF (936 MHz) sheet resistance values are 0.3 Ω/sq, 0.4 Ω/sq, and 2.5 Ω/sq for the 2 μm, 1 μm, and 0.2 μm thick MXene films, respectively. In other words, MXene films with thicker coating have lower RF sheet resistance.

IV. SIMULATION

The transmission lines were simulated in HFSS (Fig. 2d) in two different ways using: i) conductivity and DC thickness, and ii) RF sheet impedance.

A. CONDUCTIVITY AND DC THICKNESS-BASED SIMULATION

The two-port microstrip transmission line model was recreated in HFSS for simulation. Two 50 Ω lumped ports
were used to feed the transmission line. The frequency range of the simulation is 0.9-1.4 GHz, where the transmission line is electrically small compared to the wavelength. In the conductivity-thickness method, measured MXene layer thickness and approximate conductivity values were assigned to the top layer of the transmission line. The assigned conductivity was varied until the $S$-parameters were matched. Reflection-corrected $S_{21}$ was used to compare different samples. The term ‘reflection-corrected $S_{21}$’ instead of ‘attenuation’ [3] is used to avoid ambiguity with the attenuation constant of a transmission line.

Reflection Corrected $S_{21} = 10 \log_{10} \left[ \frac{|S_{21}|^2}{(1 - |S_{11}|^2)} \right]$  \hspace{1cm} (7)

The reflection-corrected $S_{21}$ was used since it includes both $S_{11}$ and $S_{21}$. Different groups of transmission lines would demonstrate different input impedance and consequently different $S_{11}$. In that case, true $S_{21}$ will not represent the power transmitted from one port to another. Reflection-corrected $S_{21}$ includes the reflection ($S_{11}$) and implies that all the power delivered to the transmission line is transmitted through the transmission line and no power is being reflected. As a result, all the transmission line groups are given equal delivered power levels. At DC, the entire volume of a conductor is used to conduct electrons. As a result, the term ‘DC thickness’ is analogous to the physical thickness of MXene coating. However, at radio frequencies, the depth of penetration (skin depth) is reduced due to the skin effect. Skin depth ($\delta$) can be calculated using the following equation [20],

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}}$$  \hspace{1cm} (8)

where $\omega$, $\mu_0$, $\mu_r$, and $\sigma$ are angular frequency, magnetic permeability of free space ($4\pi \times 10^{-7}$ H/m), relative permeability of the material, and conductivity, respectively. At 936 MHz, the skin depth of a conductor with
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35,000 S/cm is 8.79 µm (assuming $\mu_r = 1$). If the thickness of the conductor is larger than δ, the effect of thickness increase will not be prominent. This is because the RF current will not penetrate beyond δ. As a result, reflection-corrected $S_{21}$ will not change considerably. For this reason, three thickness levels were chosen below the skin depth (8.79 µm) of MXene at 936 MHz: 2 µm, 1 µm, and 0.2 µm. The entire thickness of the top MXene layer is used to carry RF currents for all three sample groups.

B. RF SHEET RESISTANCE-BASED SIMULATION

Besides conductivity-thickness simulations, conductive surfaces can be defined as an ‘impedance’ type boundary in HFSS. The transmission lines were also simulated by assigning sheet impedance values. The advantage of using sheet impedance instead of conductivity and thickness is that only transmission line measurements are needed for extracting sheet resistance while the conductivity-thickness model requires the measurement of DC conductivity and MXene thickness. Sheet resistance is the dominant parameter that determines the characteristics of $S_{21}$ compared to sheet reactance [12]. Sheet resistance represents the losses in the transmission line while sheet reactance is responsible for the reactive power in the structure. An approximate value (1.5 Ω/sq) of sheet reactance was used and the sheet resistance values were received from the extraction shown in section III. Moreover, since a common value of sheet reactance was used for both copper and MXene transmission lines, the approximation will not affect the relative comparison between different groups.

V. RESULTS AND DISCUSSION

In this work, the RF sheet resistance of MXene was extracted by measuring $S$-parameters of two-port microstrip transmission lines. As a result, the validation of the method also revolves around the $S$-parameters. $S$-parameters can be obtained from four different sources: i) Network analyzer measurement, ii) DC conductivity and thickness-based simulation, iii) RF sheet impedance-based simulation, and iv) reconstruction with extracted RLGC parameters. Fig. 9 shows the reflection-corrected $S_{21}$ of both copper and three MXene groups obtained from the first three methods. In Fig. 9, it is evident that the $S$-parameters are well matched for the copper and 2 µm thick, and 1 µm thick MXene samples. For the 0.2 µm thick MXene sample, the measured and conductivity-thickness simulated $S$-parameters are well-matched, while the extracted RF sheet resistance-based (2.5 Ω/sq) reflection-corrected $S_{21}$ is slightly deviated by around 0.34 dB from the measured value (−3.12 dB) at 936 MHz. The 0.2 µm thick sample of MXene is almost optically transparent and is difficult to maintain at a uniform thickness throughout the entire surface. As a result, the small deviation can be attributed to non-ideal fabrication and measurement errors. The RF conductivity of MXene is found to be 35,000 S/cm, which is close to the previously found value of 30,000 S/cm [2] (Fig. 10). From four-point probe measurements, the DC conductivity of MXene was found between 10,000 - 15,000 S/cm. On the other hand, since the three MXene films (2 µm, 1 µm, and 0.2 µm) were thinner than their approximate skin depth at 936 MHz (8.79 µm), for a constant conductivity (DC and RF), their sheet resistance values should be similar at both DC and RF. However, the sheet resistance values of the three samples are lower at RF (Fig. 10). These results are possible only if MXene has elevated conductivity at RF. This demonstration of anomalous RF conductivity of MXene is an extraordinary feature, making it outstanding among other conductive nanomaterials (e. g. graphene, carbon nanotubes, etc.).
The superior RF conductivity of MXene might be attributed to the accordion-type layered structure (Fig. 11) which makes it a unique conductive nanomaterial. Possible mechanisms, such as electron tunneling, and inter-layer interactions need to be studied for a complete understanding of the behavior of MXene at radio frequencies. It is also equally important to investigate the impact of flake size, inter-flake separation, and inter-layer distance on the RF conductivity of MXene.

VI. CONCLUSION

In summary, we show the anomalous conductivity and sheet resistance of Ti$_3$C$_2$T$_x$ MXene at radio frequencies. At RF, MXene demonstrates higher conductivity and lower sheet resistance compared to DC. Two-port MXene microstrip transmission lines with different thickness levels (lower than the skin depth) were constructed. RLGC-parameters were extracted from measured S-parameters and the sheet resistance values were calculated at the desired frequency.

The superior RF conductivity of MXene can open up numerous applications including 5G, IoT, wearable electronics, electromagnetic shielding, satellites, etc.

ACKNOWLEDGMENT

Any opinion, findings, and conclusion or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors would like to thank Roman Rakhmanov, Meikang Han, and Yury Gogotsi for their support with material preparation and experimentation. The synthesis of MXene was supported by Murata Manufacturing Company Ltd., Japan, and the development of MXene transmission lines described in this article was supported by Drexel University through the Charles T. and Ruth M. Bach professorship and Checkpoint Systems Company, USA. The authors thank Kyle Matthews from the A. J. Drexel Nanomaterials Institute, for his assistance in the observation of MXene morphology.

REFERENCES

[1] M. Naguib, M. Kurtoglu, V. Presser, J. Lu, J. Niu, M. Heon, L. Hultman, Y. Gogotsi, and M. W. Barsoum, “Two-dimensional nanocrystals produced by exfoliation of Ti$_3$AlC$_2$,” Adv. Mater., vol. 23, no. 37, pp. 4248–4253, 2011.

[2] M. Han, Y. Liu, R. Rakhmanov, C. Israel, M. A. S. Tajin, G. Friedman, V. Volman, A. Hoorfar, K. R. Dandekar, and Y. Gogotsi, “Solution-processed Ti$_3$C$_2$Tx MXene antennas for radio-frequency communication,” Adv. Mater., vol. 33, no. 1, Jan. 2021, Art. no. 2003225.

[3] A. Sarycheva, A. Polemi, Y. Liu, K. Dandekar, B. Anasori, and Y. Gogotsi, “2D titanium carbide (MXene) for wireless communication,” Sci. Adv., vol. 4, no. 9, Sep. 2018.

[4] F. Shahzad, M. Alhabe, C. Hatter, and B. Anasori, “Electromagnetic interference shielding with 2D transition metal carbides (MXenes),” Science, vol. 353, no. 6304, pp. 1137–1140, Sep. 2016.

[5] S. Uzun, M. Han, C. J. Strobel, K. Hantanasirisakul, A. Goad, D. Gion, and Y. Gogotsi, “Highly conductive and scalable Ti$_3$C$_2$T$_x$-coated fabrics for efficient electromagnetic interference shading,” Carbon, vol. 174, pp. 382–389, Apr. 2021.

[6] J. Lipton, J. A. Röhr, V. Dang, A. Goad, K. Mallesi, F. Lavini, M. Han, E. H. R. Tsai, G.-M. Weng, J. Kong, E. Riedo, Y. Gogotsi, and A. D. Taylor, “Scalable, highly conductive, and micropatternable MXene films for enhanced electromagnetic interference shielding,” Matter, vol. 3, no. 2, pp. 546–557, Aug. 2020.

[7] J. Zhang, N. Kong, S. Uzun, and A. Levitt, “Scalable manufacturing of free-standing, strong Ti$_3$C$_2$Tx MXene films with outstanding conductivity,” Adv. Mater., vol. 32, no. 23, 2020, Art. no. 2001093.

[8] D. Zhou, M. Han, B. Sidnawi, Q. Wu, Y. Gogotsi, and B. Li, “Ultrafast assembly and healing of nanomaterial networks on polymer substrates for flexible hybrid electronics,” Appl. Mater. Today, vol. 22, Oct. 2021, Art. no. 100956.

[9] K. AlHassou, M. Han, Y. Malallah, V. Ananthakrishnan, R. Rakhmanov, W. Reil, Y. Gogotsi, and A. S. Daryoush, “Conductivity extraction of thin Ti$_3$C$_2$T$_x$ MXene films over 1–10 GHz using capacitively coupled test fixture,” Appl. Phys. Lett., vol. 116, no. 18, May 2020, Art. no. 184101.

[10] M. A. S. Tajin, A. S. Levitt, Y. Liu, C. E. Amanatides, C. L. Schauer, G. Dion, and K. R. Dandekar, “Extraction of knitted RFID antenna design parameter from transmission line measurements,” in Proc. IEEE Int. Symp. Antennas Propag. North Amer. Radio Sci. Meeting, Jul. 2020, pp. 1551–1552.

[11] RF Sheet Resistance Extraction Code. Accessed: Jan. 25, 2022. [Online]. Available: https://github.com/drexelwireless/RF-sheet-resistance

[12] M. A. S. Tajin, A. S. Levitt, Y. Liu, C. E. Amanatides, C. L. Schauer, G. Dion, and K. R. Dandekar, “On the effect of sweat on sheet resistance of knitted conductive yarns in wearable antenna design,” IEEE Antennas Wireless Propag. Lett., vol. 19, no. 4, pp. 542–546, Apr. 2020.
M. A. S. Tajin, K. R. Dandekar: Anomalous Radio Frequency Conductivity and Sheet Resistance of 2D Ti$_3$C$_2$Tx MXene

[13] J. L. Hart, K. Hantanasirisakul, A. C. Lang, B. Anasori, D. Pinto, Y. Pivak, J. T. van Omme, S. J. May, Y. Gogotsi, and M. L. Taheri, “Control of MXenes' electronic properties through termination and intercalation,” Nature Commun., vol. 10, no. 1, pp. 1–10, Dec. 2019.

[14] A. Iqbal, P. Sambyal, J. Kwon, M. Han, J. Hong, S. J. Kim, M.-K. Kim, Y. Gogotsi, and C. M. Koo, “Enhanced absorption of electromagnetic waves in Ti$_3$C$_2$T$_x$ MXene films with segregated polymer inclusions,” Compos. Sci. Technol., vol. 213, Sep. 2021, Art. no. 108878.

[15] B. Xu, M. Zhu, W. Zhang, X. Zhen, Z. Pei, and Q. Xue, “Ultrathin MXene-micropattern-based field-effect transistor for probing neural activity,” Adv. Mater., vol. 28, pp. 3333–3339, Feb. 2016.

[16] C. Liu, S. Hao, X. Chen, B. Zong, and S. Mao, “High anti-interference Ti$_3$C$_2$T$_x$ MXene field-effect-transistor-based alkali indicator,” ACS Appl. Mater. Interface, vol. 12, no. 29, pp. 32970–32978, 2020.

[17] M. Alhabeb, K. Maleski, B. Anasori, P. Lelyukh, L. Clark, S. Sin, and Y. Gogotsi, “Guidelines for synthesis and processing of two-dimensional titanium carbide (Ti$_3$C$_2$T$_x$ MXene),” Chem. Mater., vol. 29, no. 18, pp. 7633–7644, 2017.

[18] R. Papazyan, P. Pettersson, H. Edin, R. Eriksson, and U. Gafvert, “Extraction of high frequency power cable characteristics from S-parameter measurements,” IEEE Trans. Dielectr. Electr. Insul., vol. 11, no. 3, pp. 461–470, Jun. 2004.

[19] K. Kiziloglu, N. Dagli, G. L. Matthaei, and S. I. Long, “Experimental analysis of transmission line parameters in high-speed GaAs digital circuit interconnects,” IEEE Trans. Microw. Theory Techn., vol. 39, no. 8, pp. 1361–1367, Aug. 1991.

[20] D. M. Pozar, Microwave Engineering. Hoboken, NJ, USA: Wiley, 2012.

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