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Supplementary Materials for

2D titanium carbide (MXene) for wireless communication

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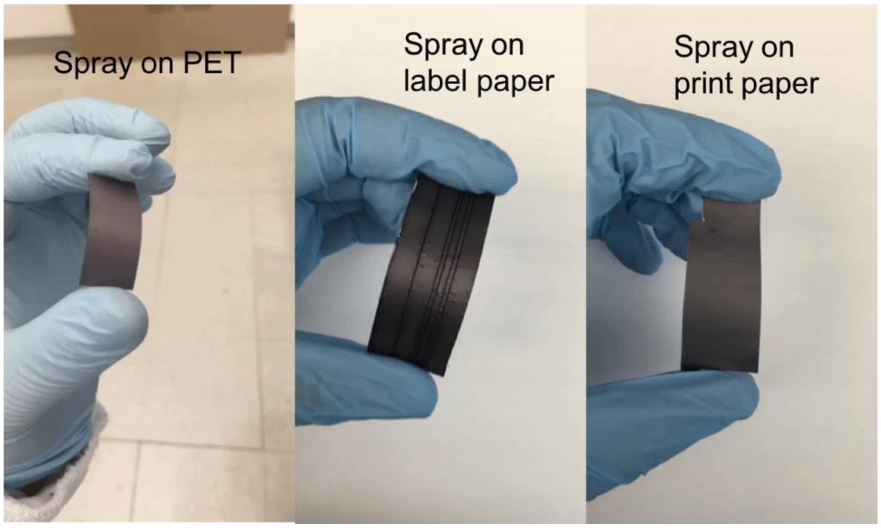

Fig. S1. Photo of thick MXene film sprayed on PET, label paper, and printing paper.

Ti_3C_2 spraying on paper substrates

To show the variety substrates that can be potentially used, we sprayed MXene on various paper types pre-cut by laser: "*resume"* (Southworth 100% Cotton Resume Paper, 8.5" x 11", 32 lb., Wove Finish, White), *"printing"* (Boice X9 20 lb./75 gsm/10M), *"thesis"* (Southworth Thesis Paper, 8.5" x 11", Wove Finish, Bright White), and *"label"* paper (Avery 8160). Spraying was complicated due to wetting and deforming of the paper during the spraying process. Several samples were prepared: paper substrates were cut in rectangular shapes of 5 by 5 cm^2 which were cut after spraying process into TLs and antennas. In order to keep the same conditions, spraying was done at the same time for all the substrates. In Table S1, data on sheet resistance obtained from various papers are presented.

Table S1. Sheet resistance of Ti_3C_2 MXene sprayed on paper.

Paper type	Sheet resistance (Ohm/sq)
Print	11 ± 6
Resume	7 ± 1
Thesis	47 ± 14
Label paper	1.1 ± 0.2

The lowest resistance was reached by using the "label" paper. However, label paper shows several wrinkles and lifted-off regions (Fig. S1), which can disrupt the conductive pathway. Determining the thickness for those samples was complicated due to the wetting and penetration of MXene through porous paper. However, in future, paper may be used as a cheap and flexible substrate.

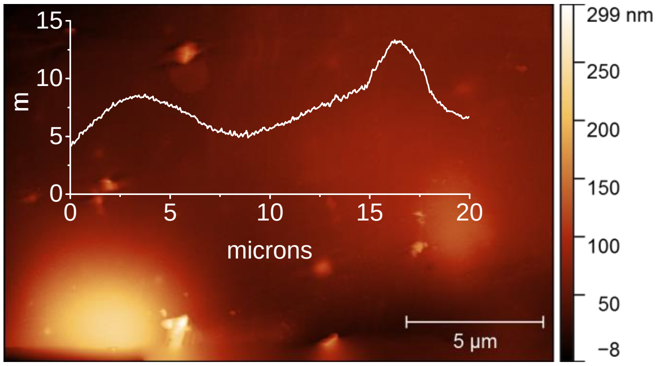

Fig. S2. AFM image of PET.

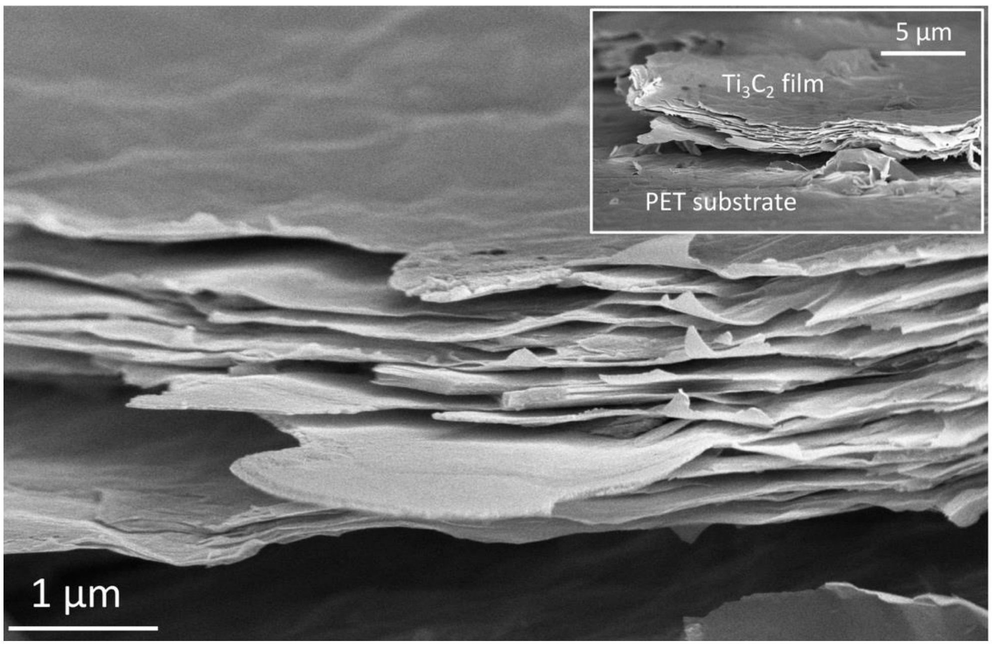

Fig. S3. SEM image of a MXene Ti_3C_2 antenna cross section. We fractured a Ti_3C_2 film antenna sprayed on PET to demonstrate its cross-section. The cross-section shows individual MXene flakes were restacked to form the film during spraying. The inset shows the same cross-section at lower magnification. The fractured cross-section is partially peeled off.

Skin depth

In order to understand the meaning of the skin depth, one should understand how the current flows through the conductor. The alternating current (AC) applied to the conductor by a transmitter creates an oscillating electric and magnetic field in the conductor. This phenomenon leads to radiation of energy away from the conductor into space as a moving transverse electromagnetic field wave. On the other hand, during reception, the AC of an incoming radio wave resonates with the conductor, leading to the oscillation of the electrons which creates a current inside the conductor. This electric current passing through a conductor tends to be distributed near to the surface, as determined by the skin depth of the material. The equation is given below (*2*):

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

where δ is a skin depth, ρ is resistivity, f is frequency of the current, μ is permeability of the material. At direct current (DC), electric current flows uniformly through a conductor. This means the current density is the same everywhere. In AC the current density actually drops off exponentially from the surface. It can be illustrated by the equation below (*2*):

$$J = J_0 e^{(-\frac{z}{\delta})}$$

where J is a current density, δ is a skin depth and z is a distance from the surface. While the thickness of the conductor decreases, the total current density decreases as well leading to the increase of the losses.

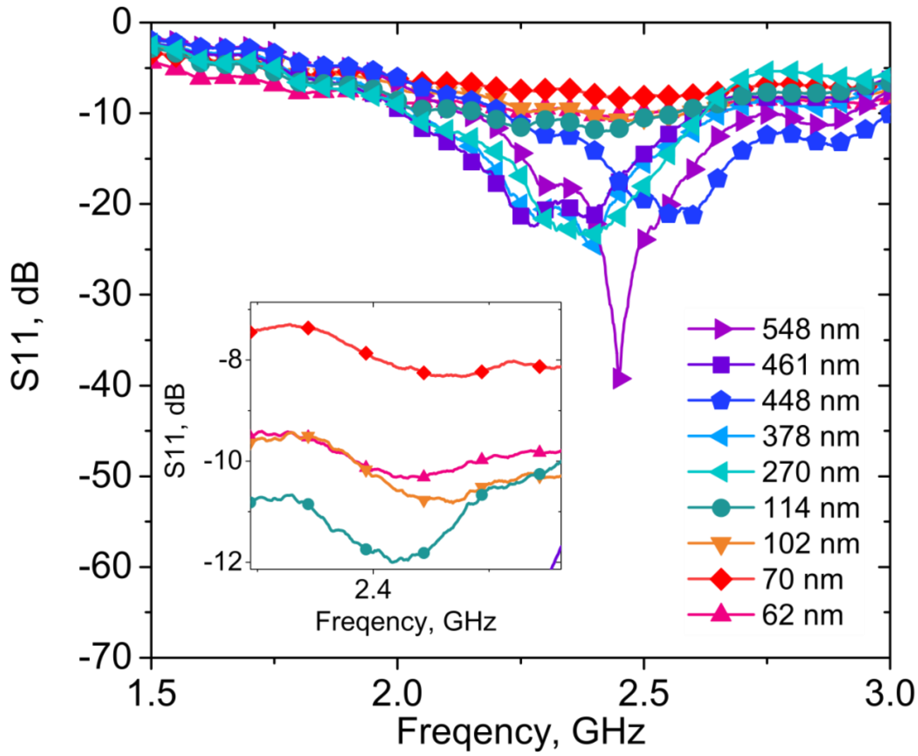

Fig. S4. Reflection coefficient of Ti_3C_2 MXene. These reflection coefficients were measured on sprayed Ti_3C_2 antennas with thicknesses between 62 to 548 nm.

Table S2. Comparison of the return loss of MXene dipole antennas with other materials. Metal ink, graphene, carbon nanotubes (CNT), onion like carbon (OLC), conductive polymers (PEDOT-PSS, PANI), transparent conductive oxides (ITO)

Material	Antenna type	thickness (μm)	|Return loss| (dB)	sheet resistance (Ohm/sq)	Reference
Ti_3C_2 MXene	Dipole antenna	8	65	0.02 ± 0.003	This work
	Dipole antenna	1.4	36	0.77 ± 0.08	
	Dipole antenna	0.548	39	2.26 ± 0.28	
	Dipole antenna	0.461	22	3.85 ± 0.31	
	Dipole antenna	0.448	21	4.13 ± 0.15	
	Dipole antenna	0.378	24	5.27 ± 0.26	
	Dipole antenna	0.270	23	8.5 ± 0.8	
	Dipole antenna	0.114	12	18.4 ± 1.7	
	Dipole antenna	0.102	11	25.6 ± 2.2	
	Dipole antenna	0.070	8	43 ± 10	
	Dipole antenna	0.062	10	47 ± 8	
Cu foil	Dipole antenna	50	42	0.00021	
Cu foil	Dipole antenna	10	23	0.001344	
Cu foil	Dipole antenna	6.5	31	0.0024	
Al foil	Dipole antenna	80	33	0.00141	
Al foil	Dipole antenna	12	24	0.00282	
Al foil	Dipole antenna	7	10	0.0043	
Silver ink	Dipole antenna	4	50	0.017	*34*
Silver nanopaste	Dipole antenna	12	47	0.003	*35*
Copper	Dipole antenna	31	28		*35*
PEDOT-PSS	Dipole antenna	25	15	1200	*4*
Silver ink	Dipole antenna	1.5	19	3.6	*36*
Silver ink	Dipole antenna	3	27	3.1	*36*
Silver ink	Dipole antenna	7.5	21	16	*36*
Au/CNT on textiles	Patch antenna		22	2	*37*
MWCNT-PDMS-Au	Patch antenna	1	20	10	*38*
MWCNT	Dipole antenna	25	30	5.9	*8*
MWCNT ink	Patch antenna	500	28.5	110	*39*
ITO	Monopole antenna		23	10	*40*
CNP@Pt PANI	Dipole antenna	50	37.4	3	*41*
C/PANI	Monopole antenna	50	18.5	2.5	*42*
CNT	Dipole antenna	250	10	0.2	*6*
OLC	Dipole antenna	250	10	0.04	*6*
Graphene	Patch antenna	25	17	4.8	*43*
Silver ink	Dipole antenna	50	29	0.041	*44*
Graphene	Dipole antenna	25	15	4	*44*
Graphene	Dipole antenna	7.7	12	8.2	*12*

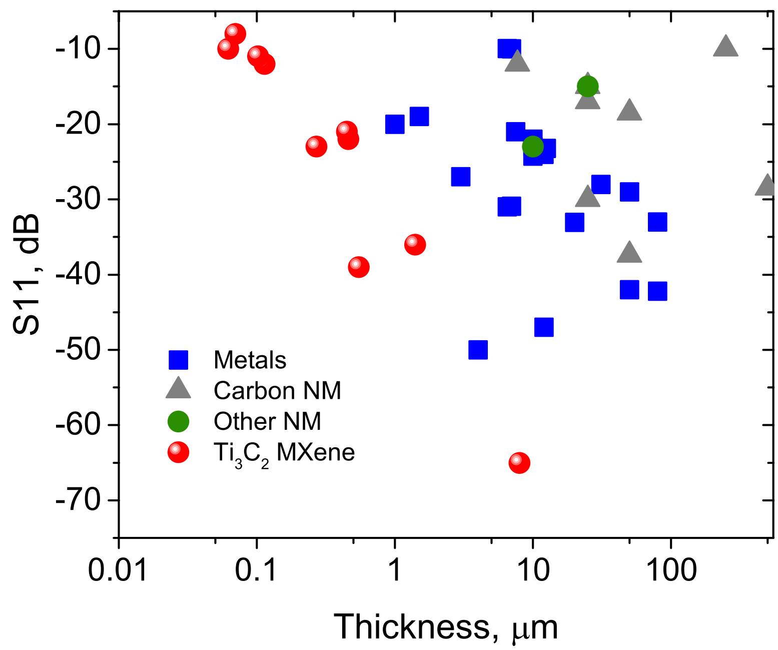

Fig. S5. Comparison of the return loss of MXene dipole antenna with metals, carbon nanomaterials, conductive polymers, and transparent conductive oxides. Data are taken from the table S2. Ti_3C_2 MXene results are presented as red circles.

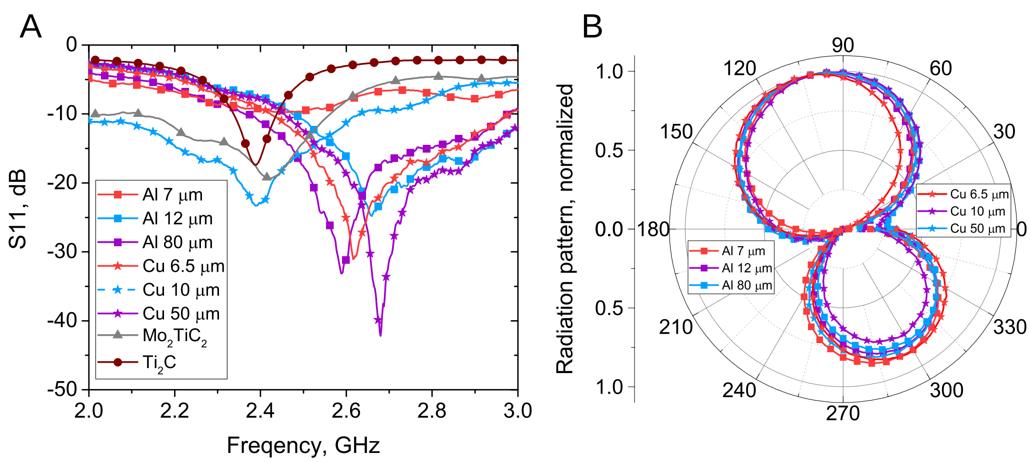

Fig. S6. Characteristics of dipole antennas made of Mo_2TiC_2, Ti_2C MXenes, and metal foils. (A) Reflection coefficient of antennas made of aluminum, copper foil and different MXenes compositions (Ti_2C and Mo_2TiC_2). (B) Normalized radiation pattern of metal foil antennas.

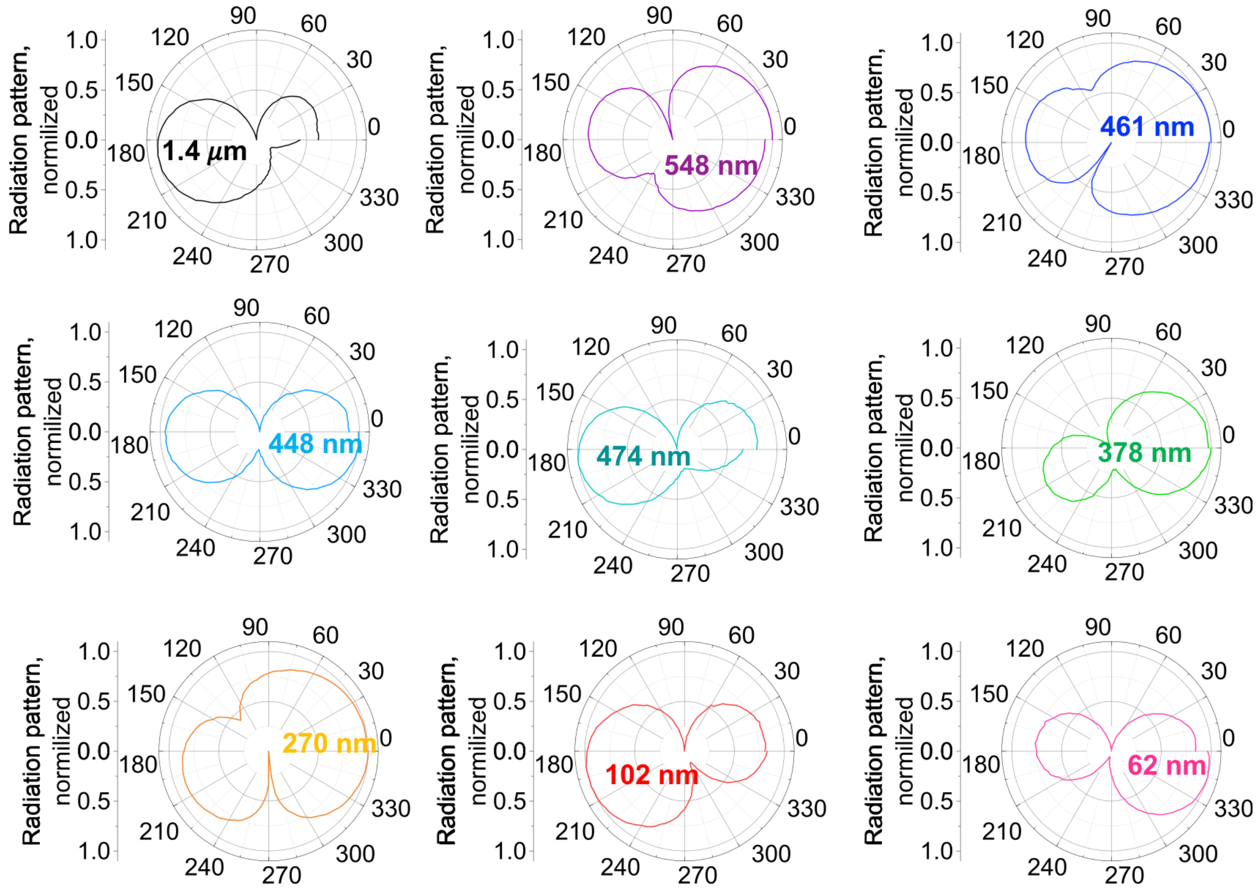

Fig. S7. Normalized radiation pattern of Ti_3C_2 MXene sprayed film antennas. MXene film thickness in each antenna is shown on each plot.

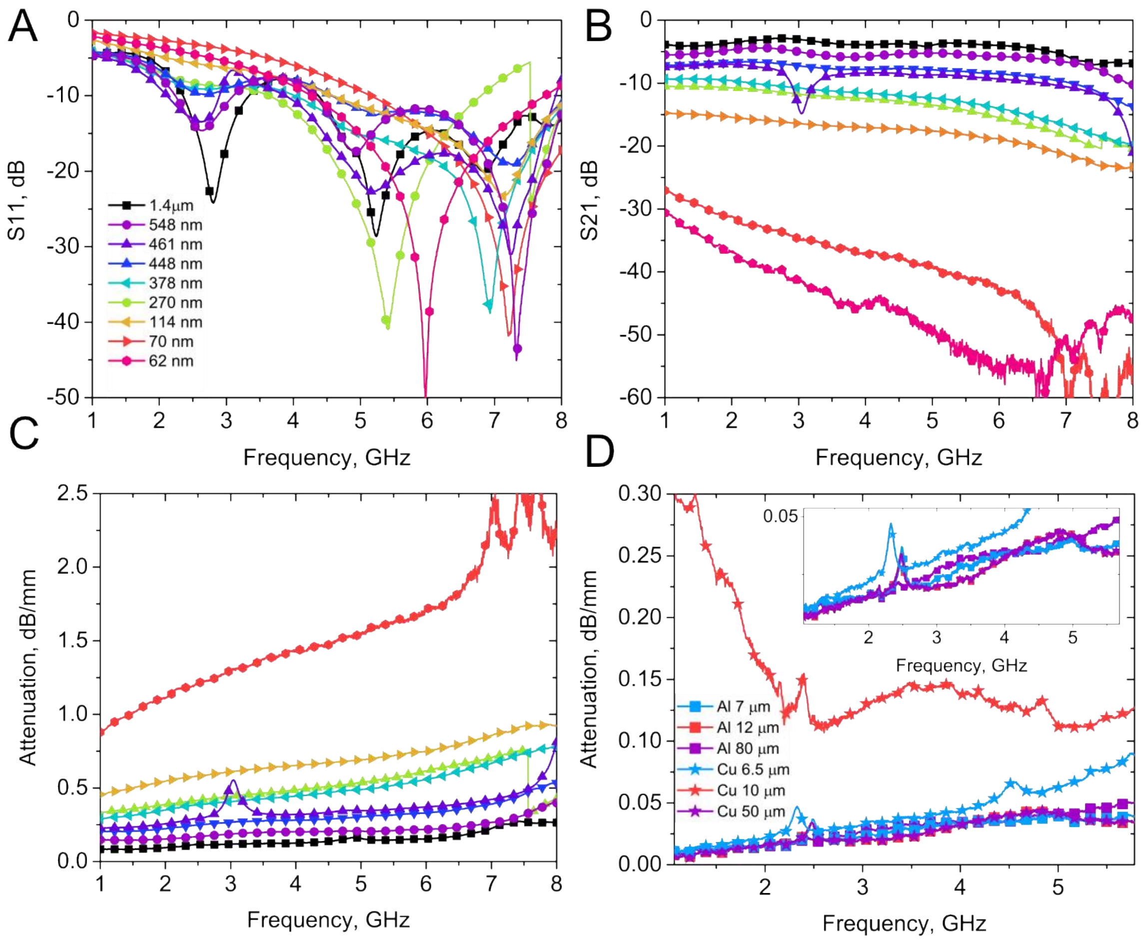

Fig. S8. Characteristics of transmission lines made of MXene Ti_3C_2 and metal foils. S_{11} (reflection, **A**), S_{21} (transmission, **B**) and attenuation (**C**) of sprayed thin-film MXene antennas in the region from 1 to 8 GHz. Attenuation (**D**) of transmission lines made of metal (aluminum and copper) foils.

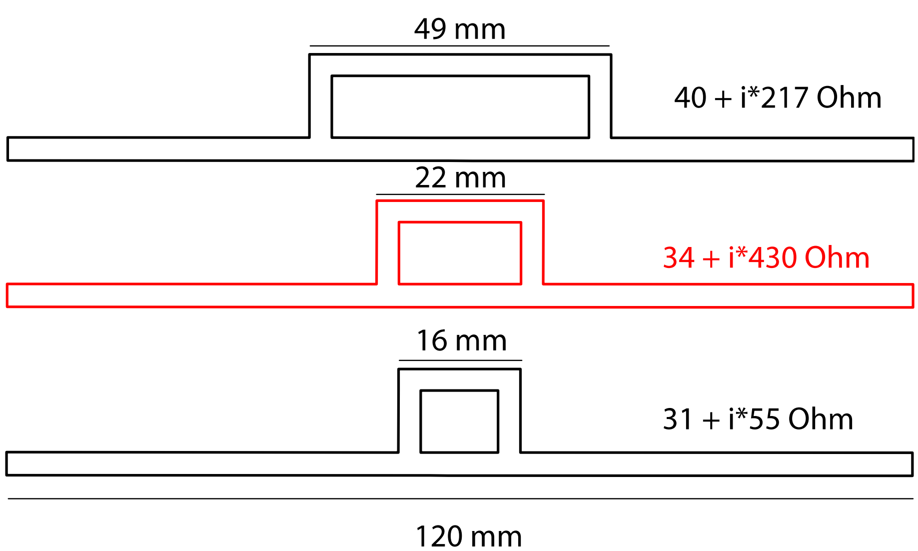

Fig. S9. Dimensions of RFID antennas made of Ti_3C_2 MXene. Red is attributed to the design with the closest impedance matching and therefore the longest reading range (8 meters).