Supplemental Document

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Directly drawing metamaterials on paper based on an automatic drawing machine: supplement

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1. Physical parameters' optimization of the polarization converter

Before optimization, the effect of the physical parameters on the cross-polarized transmission curves needs to be clarified. Here, six parameters (g_1, g_2, h_1, h_2, l, and w) are analyzed through simulation, as shown in Fig. S1. The effects of different parameters are discussed as follows:

(1) The parameter g_1: From Fig. S1(a), it can be seen that the transmission bandwidth increases while the amplitude may decrease to less than 0.9 as the parameter g_1 changes from 8.25 mm to 10.25 mm.

(2) The parameters g_2 and w: From Fig. S1(b), it can be seen that the parameters g2 and w mainly impact the transmission bandwidth. When g_2 changes from 8.0 mm to 10.0 mm or w changes from 5.0 mm to 7.0 mm, the transmission bandwidth increases while the transmission amplitude basically keeps the same.

(3) The parameters h_1 and h_2: The effect of the parameters h_1 and h_2 on the transmission curves is similar, as shown in Fig. S1(c) and (d). The transmission bandwidth increases while the amplitude may decrease to less than 0.9 as the parameter h_1 or h_2 changes from 2.0 mm to 4.0 mm.

(4) The parameter l: From Fig. S1(e), it can be seen that parameter l mainly impacts the transmission amplitude. When l changes from 25.6 mm to 27.6 mm, the transmission amplitude decreases around 4 GHz while the transmission bandwidth is essentially unchanged.

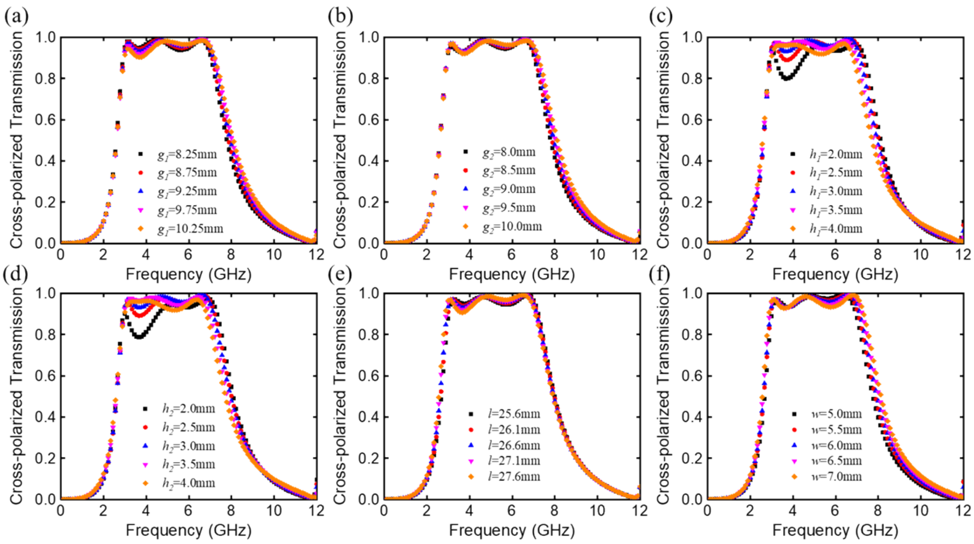

Figure S1. The simulated cross-polarized transmission. (a) The parameter g_1 changes from 8.25 mm to 10.25 mm; (b) The parameter g_2 changes from 8.0 mm to 10.0 mm; (c) The parameter h_1 changes from 2.0 mm to 4.0 mm; (d) The parameter h_2 changes from 2.0 mm to 4.0 mm; (e) The parameter l changes from 25.6 mm to 27.6 mm; (f) The parameter w changes from 5.0 mm to 7.0 mm.

Based on the above analysis, the physical parameters are selected appropriately and then adjusted according to the simulation results and the feasibility of sample fabrication. The final physical parameters are optimized as h_1 = 3 mm, $h2$ = 3 mm, g_1 = 9.25 mm, g_2 = 9 mm, w = 6 mm, and l = 26.6 mm.

2. Physical parameters' optimization of the absorber and coding metasurface

During the design process of the unit-cell, physical parameters need to be adjusted according to the electromagnetic response. However, there is always a complex and nonlinear relationship between the physical parameters of a unit-cell and its electromagnetic response, which makes the optimization process of parameters complicated and tedious. Therefore, when there are too many parameters, to improve the design efficiency and simplify the design process, the genetic algorithm is utilized to optimize the parameters automatically.

Genetic algorithm is a method of searching for optimal solutions by simulating natural evolutionary processes [1]. The flow chart of the MATLAB optimization program based on a genetic algorithm is shown in Fig. S2. Before running the program, the parameters need to be optimized, and the parameters of an initial individual are entered. Once the program starts running, it will take random values within the variation of the optimization parameters to get the initial population. The program then calls the full-wave simulation software, enters the appropriate parameters, and performs a simulation to obtain the desired objective function's values. Before starting the program, a maximum number of population generations can be set, and if this number is not reached, the program will continue to run. Each subsequent generation of the population is based on the good individuals of the previous generation through three processes of replication, crossover, and mutation.

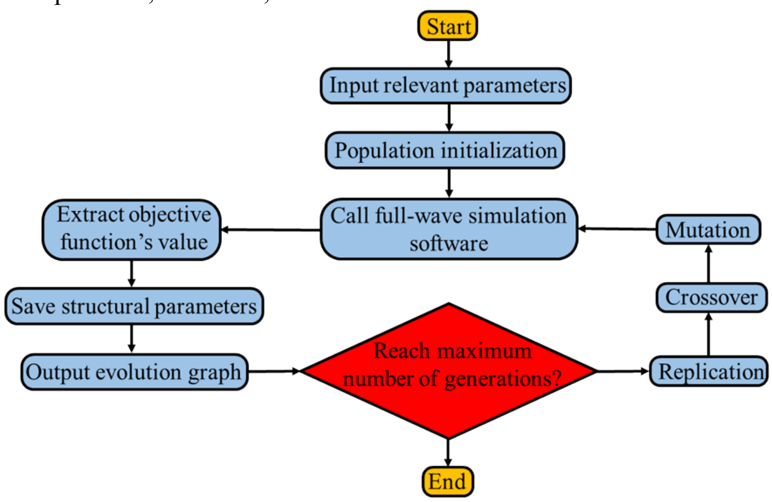

Figure S2. The flow chart of the MATLAB optimization program based on a genetic algorithm.

The unit-cells of the paper-based absorber and conformal coding metasurface are optimized through the MATLAB optimization program based on a genetic algorithm. After optimization, the effects of the physical parameters on simulation results can be further analyzed to ensure a good result.

3. Analysis of the angle *θ*

After the optimization of the genetic algorithm, the effect of the physical parameters on the simulation results of the unit-cell can be further analyzed. Here, take the angle θ in the coding metasurface as an example. As shown in Fig. S3(a), as θ changes from 106° to 126°, the second resonant frequency around 5 GHz becomes higher, resulting in the decrease of the bandwidth. Moreover, the co-polarized reflection coefficient becomes smaller around the second resonant frequency. Meanwhile, the cross-polarized reflection coefficient stays the same when θ changes from 106° to 126°, while the bandwidth decreases slightly, as shown in Fig. S3(b). It can be seen in Fig. S3(c) that the phase difference of two 1-bit unit-cells is kept at about 180° as θ

changes from 106° to 126°. Considering all the effects that the angle θ brings to the performance of the unit-cell, its value was finally determined as 116°.

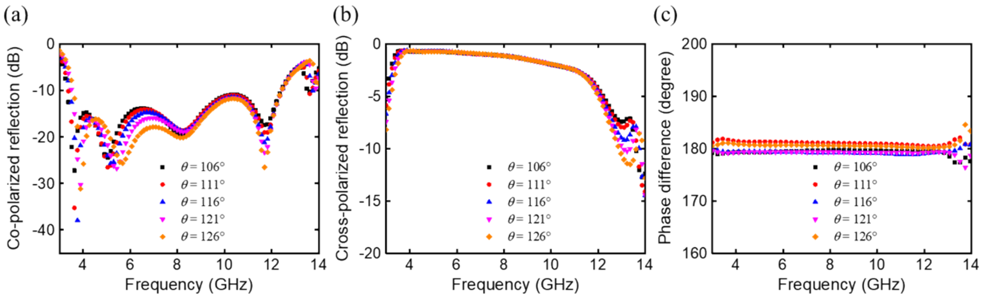

Figure S3. Simulated results of the unit-cell when the angle θ changes from 106° to 126°. (a) The co-polarized reflection; (b) The cross-polarized reflection; (c) The phase difference.

4. Comparison with previous works

The most fundamental difference between this work and previous works, like Refs. [2], [3] and [4], is that the drawing technology was utilized to fabricate the samples in this work while others used PCB or photolithography technology, as shown in Table S1. This difference makes our work have the advantage of being economical, flexible, eco-friendly, and easily fabricated. Moreover, by using paper as the dielectric substrate, the fabricated samples are inherently light and conformable. Therefore, compared with Refs. [2] and [3], our work has the advantages of being lightweight, flexible, and eco-friendly. Compared with Ref. [4], our work has the advantages of being economical and easily fabricated. In addition, three different types of metamaterials were fabricated and measured to demonstrate the feasibility of the drawing technology, this means that we may be able to realize more functions in metamaterials with this technology in the future.

Table S1. Comparison with Previous Works

Work		Fabrication technology	Dielectric	Functionality	Conformal
Ref. [2]		PCB technology	F4B	Beam control	No
Ref. [3]		PCB technology	/	Metalen	No
Ref. [4]		Photolithography	Polyimide	Diffuse scattering	Yes
Our work	1	The drawing technology	Paper	Polarization converter	Yes
	2			Absorber	Yes
	3			RCS reduction	Yes

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