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***Abstract* — This paper presents optically transparent dipole antennas with innovative meshes for printing processes. The influence on antenna performance of the meshing geometry, the width and the pitch of dipole are investigated. The study shows that, for a given width, an increase of the performance with a twin small pitch with circle geometry. Furthermore, the antennas with an optical transparency of 70% present a loss of the realized gain around 0.35% compared to an opaque conventional dipole antenna with the same width.**

***Keywords* — Transparent antennas; Meshed antennas; Dipole antennas; Printed Antennas**

I. INTRODUCTION

Nowadays, antennas and Internet of Things (IoT) present an important part of the economy and lifestyle in the world. The development of transparent antennas is a new challenge to tend new markets, especially in smart packaging or smart building. Besides, the uses of additives processes to produce those types of antennas like screen-printing or ink-jet provide an innovative touch and new conveniences for flexible IoT for example. Indeed, printing processes allow the production of antennas on larger flexible substrates like polyethylene terephthalate (PET), paper by an additive process limiting the amount of product used and the environmental impact. The development of flexible antenna for energy scavenging by 3D printing in [1] allows tending new markets. The design of antenna using flexible substrate – paper- for energy harvesting at 1800MHz describe in [2] shows compact antenna with high gain.

However, one of the notable problems to develop transparent and flexible antennas by printing processes is the ratio conductivity/transparency of the conductive ink. The better is the conductivity, the less the pattern is transparent. A solution to obtain an excellent transparent film with a good conductivity is Indium Tin Oxide (ITO) (Sheet resistance Rs = 5-70 $\Omega.sq^{-1}$ for %T > 85% @550nm). ITO presents several problems which are its fragility and its implementation.

An innovative technique for the development of optically transparent antennas is the meshing method like describe in [1]. The antennas develop by meshing method have lower performance in terms of realized gain or radiation than their no-mesh homologue. In the case to obtain meshed antennas with a loss of performance as low as possible and the best transparency, the geometry of the meshing is studied here with four different types: honeycomb, square, diamond and circle (Fig. 1b).

An important point with this meshing is the size of the pitch. Indeed, a relation linking the wavelength λ_0, the size of the pitch and the performance has been developed in [4].

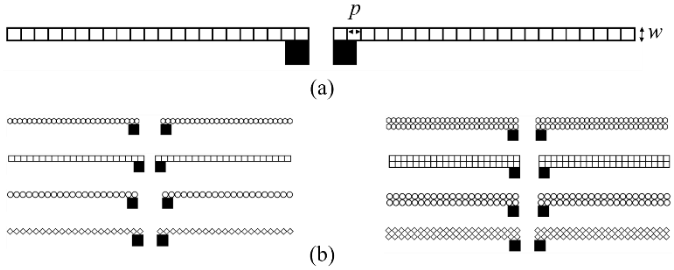

Fig. 1:(a) Geometry of a mesh square dipole antenna with a pitch *p* and a width *w*. (b) Design of dipole antenna with different width *w* and mesh geometry: honeycomb, square, circle and diamond. On the left, the first type for *w/2*. On the right, the second type for *w*.

Based on the characteristic of an additive printing process, the screen printing, developed in the next section, the study of the antenna design will be discussed. For that, the comparison of the mesh geometries and the pitch inside the mesh will be realized.

II. PRINTING PROCESSES

To develop those antennas, the specifications of an additive printing process must be considered. In this case, the technique of screen printing was chosen. It is a process which can be used on an industrial scale, for its high productivity, its repeatability and it is an additive technique, so environmentally friendly.

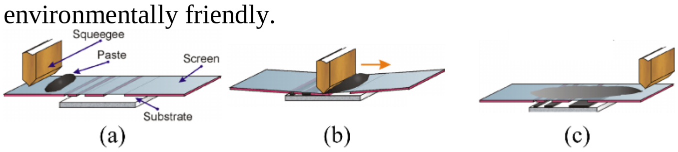

Fig. 2 : Scheme of the screen printing. (a): before printing. (b): printing. (c): after printing

The screen printing process is described in fig. 2. First, the conductive paste is deposited on a screen with the designed antenna (fig.2a). The substrate is below the screen. Then, with a squeegee, the paste is transferred on the substrate according the scheme on the screen by a short and thin contact between the screen and the substrate (fig. 2b). It is important to underline that the speed and the tilt of the affect the accuracy of the pattern. At the end, after the passing of the squeegee, the squeegee removes the ink and a new substrate is placed below the screen to start a new printing (fig. 2c).

One of the most important points with the screen printing is the screen itself. It is composed of polyester thread with a given density and diameter. If the density of thread is important, then the quantity of ink passing inside the screen is low and thus the thickness too. The minimal width is given by the diameter of the thread. It is established than the minimal width is equal to three times the diameter of the thread. In the case of this article, the diameter of the thread is around 34 µm; the minimal width *w* is 100 µm. The distance between the substrate and the screen, the off-contact, is important too. If the off contact is too important, the scheme will not be printed on the substrate. If it is too short, the resolution of the pattern will be affected.

To design and simulate according to those specifications, the sheet resistance of a conventional conducive ink is used for the simulations, presenting a sheet resistance R_s = 30 mΩ.sq^{-1}. The substrate used is a PET Melinex ST726 from Dupont-Teijin (thickness: 175 µm, ε_r: 2.88 @ 2.45 GHz, *tan* δ: 0.024 @ 2.45GHz).

III. Antenna Design

The antennas presented previously were designed using commercial software, CST Studio Suite. The choice of the geometry is motivated by the originality of the mesh. The feasibility of meshes square antennas was studied in [5]. The meshing in honeycomb has been developed to improve communications inside buildings in [6]. The geometry tends to improve the bandwidth and the stability of the patch. The benefit of diamond meshing obtained by sputtering was studied in [7]. The design allows an optical transparency for an equal sheet resistance compared to an opaque antenna. However, according to our research, there are no studies about meshes dipole antennas with circle or honeycomb geometry. The impact of the pitch was evaluated in [4]. Furthermore, the performance and the optical transparency of the antenna are linked to the wavelength λ_0 and the pitch following (1).

$$\frac{\lambda_0}{p} = x \tag{1}$$

The factor x must be close to 100 for a good ratio transparency/performance. A value below 100 will conduct to a very transparent antenna but underperforming. On the contrary, a value upward corresponds to an antenna with a high performance for a low transparency. In light of this, knowing the wavelength λ_0 for our application, the pitch *p* and the strip width *s* is defined.

The dimensions are given in Table 1. The optical transparency in the light visible spectrum has been calculated from (2):

$$T(\%) = [(p - s)/p]^2 . T_{sub} \tag{2}$$

T_{sub} is the optical transparency of the substrate used (0.87 or 87%). The strip width *s* is the same for all antennas due to the printing processes. The value of the pitch changes according to the antennas. They are composed of a single or a twin line of meshes. The transparency is affected, from 69.65 for a single line with a total width *w/2* to 78.91 % for a single line of width *w*. The ratio x is increased slightly to 128.89 from 58.31. The first value is closer to 100, the ideal ratio for optical transparency and performance. Hence, the antenna type 1 with a width of *w/2* should present the best compromise between performance and transparency. Moreover, two squares were designed to realize an easier connection with devices easier and they are included in all following simulations.

Table 1. Mesh dimensions and transparency associated.

	Meshing		
	Antenna type 1 (w/2)	**Antenna type 2 (w)**	**Antenna type 3 (w)**
Pitch *p* (mm)	0.95	1.9	2.1
Strip width *s* (mm)	0.1	0.1	0.1
Total width *w* (mm)	1.15	2.3	2.3
Optical Transparency T (%)	69.65	78.08	78.91
Ratio x	128.89	64.45	58.31

IV. Simulation and Results

The aim of the study is to develop new type of mesh dipole antenna, produced by a printing process and optically transparent for application at the 2.45 GHz frequency. The design of those antennas was realized previously.

Based on those requirements, the realized gain is compared to the optical transparency of the antennas to investigate the influence of several geometries meshes. For this purpose, antennas were adapted by playing on the distance between each part of the antenna.

A. Reflection Coefficient $|S_{11}|$

The $|S_{11}|$ parameter is simulated for each antenna. First, the $|S_{11}|$ for a pitch of 2.1 mm and a total width of 2.3 mm is presented in fig. 3. The antennas were optimized and adapted. The adaptation is better for meshed antennas than the reference opaque antenna. It can be explained by the meshed geometry. Each geometry acts like a small resonator, increasing the signal of the antenna.

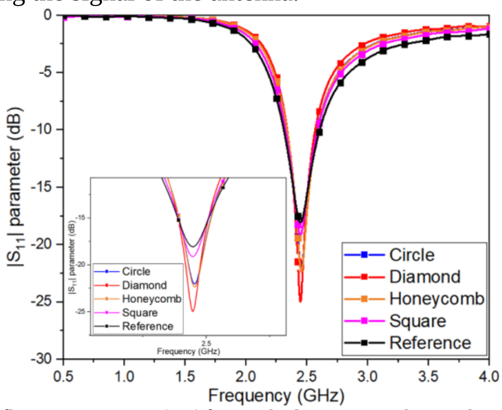

Fig. 3: Reflection parameter $|S_{11}|$ for meshed antenna with a pitch *p* of 2.1 mm and a total width *w* of 2.3 mm. In the insert, zoom of the coefficient at 2.45GHz.

Secondly, the $|S_{11}|$ for a pitch of 1.9 mm and a total width of 2.3 mm is presented in fig. 4. The adaptation at 2.45 GHz is realized and every meshed antenna presented a better signal than an opaque reference antenna. The value of $|S_{11}|$ coefficient is lower than in fig. 3, from -24.96 dB for the square in fig. 3 to -20.86 dB for the same geometry in fig. 4. In general, a decrease of around 10% of intensity is observed. Those antennas were designed with a double line of meshes with the same pitch *p*. The proximity between those lines leads to an interference between each meshes, limiting the coefficient reflection.

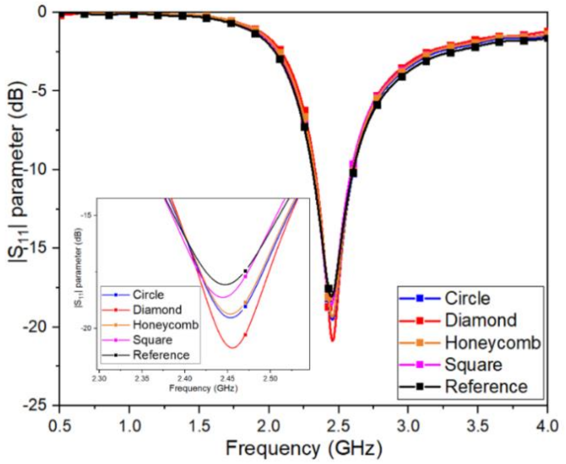

Fig. 4 : Reflection parameter $|S_{11}|$ for meshed antenna with a pitch *p* of 1.9 mm and a total width *w* of 2.3 mm. In the insert, zoom of the coefficient at 2.45GHz.

Third, the antenna with a single line of meshing for a pitch p of 0.95 mm and a total width w/2 of 1.15 mm is investigated in fig. 5. The adaptation of those antennas was realized and a decrease of the reflection coefficient is noted. This decrease of the intensity is expected because of the decrease of the pitch, limiting the resonating effect. However, the intensity stays correct with a signal $|S_{11}|< -16$ dB. The decrease of the peak intensity is around 6%, which is acceptable for a decrease by 2 of the size.

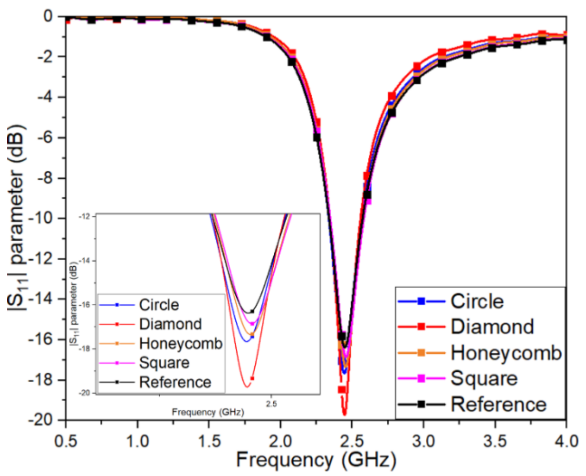

Fig. 5: Reflection parameter $|S_{11}|$ for meshed antenna with a pitch *p* of 0.95 mm and a total width *w* of 1.15 mm. In the insert, zoom of the coefficient at 2.45GHz.

B. *Realized Gain*

The design of each antenna was adapted for the frequency *f* 2.45 GHz. The realized gain of those antennas is studied in this part. The results are presented in Table 2. The realized gain by those antennas will strongly depend on the size of the pitch *p* and the width *w*.

For antennas with a pitch *p* = 0.95 mm and width *w* = 1.15 mm, the ratio *x* is 128.89 (see Table 1). The mesh antenna with the best gain is the circle followed by the honeycomb, the square and the diamond. The value observed for the realized gain confirms this model, with a realized gain between 1.85 dBi for the diamond geometry and 1.949 dBi for the circle geometry. The difference is very small, around 5%, and only 1% with an opaque reference antenna. On the contrary, the gain in optical transparency is important, from 0% to 69.65%.

For antennas with a pitch *p* = 0.95 mm and a width *w* = 2.3 mm, the best mesh antenna is the circle, followed by the honeycomb, the diamond and the square. The realized gain here is between 2.005 dBi for the circle and 1.951 dBi for the square, a loss of gain about 2.69 %. The difference with a reference antenna is between 2.57 % for the circle and 5.2 % for the square, with an optical transparency from 0% for an opaque to 78.08% for those models.

To conclude, antennas designed with a pitch *p* = 2.1 mm and a total width *w* = 2.3 mm are investigated. The realized gain changes the order of antennas. The honeycomb is the best mesh antenna with 1.906 dBi, followed by the square, 1.879 dBi, the circle, 1.87 dBi and the diamond with 1.808 dBi. Those values present a higher variation than before, with amplitude of 5.15 % between them and up to 12.15 % compared to the reference antenna. The variation in the list of best meshing can be explained by the ratio between the low contact among geometries and their high surface for meshed circle and diamond antenna.

Indeed, honeycomb and square present line in contact inside the structure, allowing a better diffusivity of the radiation in the field. The low contact between circles or diamonds creates important loss of current, thus loss of radiation. This case is in agreement with the ratio *x* calculated in Table 1, 58.31. That value is synonym of low performance but high transparency for those antennas, which is the case with an optical transparency of 78.91%.

The relation between optical transparency and realized gain shows that the difference of optical transparency between the antennas type 2 and 3 is very low, 0.83% but the loss of performance is more important. The difference between the type 1 and 2 is the optical transparency, with a smaller dispersion in terms of realized gain with the type 2 than the type 1 for the same pitch. This can be attributed to the twin line of each pattern, increasing the radiation in the field better than a single line.

Table 2: Realized Gain in dBi for meshes antennas dependant of the pitch p, the width w and the geometry

Geometry	**Pitch *p* (mm)**	**Width *w* (mm)**	**Realized Gain (dBi)**
Reference 1	0	1.15	1.970
Circle 1	0.95	1.15	1.949
Diamond 1	0.95	1.15	1.850
Honeycomb 1	0.95	1.15	1.898
Square 1	0.95	1.15	1.853
Reference 2	0	2.3	2.058
Circle 2	0.95	2.3	2.005
Diamond 2	0.95	2.3	1.972
Honeycomb 2	0.95	2.3	1.992
Square 2	0.95	2.3	1.951
Reference 3	0	2.3	2.058
Circle 3	2.1	2.3	1.870
Diamond 3	2.1	2.3	1.808
Honeycomb 3	2.1	2.3	1.906
Square 3	2.1	2.3	1.879

V. CONCLUSION

The design and the study of optically transparent meshing antennas were realized. The pitch *p*, the width *w* and the geometry were studied. Those antennas were designed to be manufactured by printing processes like screen printing on flexible substrate for IoT applications at 2.45 GHz. The adaptation of those antennas were investigated, showing an influence of the geometry and the width on the $|S_{11}|$ parameter, with a decrease from -24.96 dBi for a meshed square antenna with a width w = 2.3 mm to -19.71 dBi for a meshed square antenna with a width w = 1.15 mm. The pitch p influences greatly the optical transparency of the antenna. Lower is the pitch, lower is the optical transparency. However, lower is the pitch, better is the performance. A compromise must to be found to conserve high performance and high optical transparency. For that, the idea is to design antennas with medium pitch in twin line like antennas type 2, allowing a high transparency, 78.08% with a realized gain near an opaque and traditional antenna, 2.005 dBi for a meshed twin-circle antenna and 2.058 dBi for an opaque antenna. Honeycomb meshing is interesting for small antennas, presenting the geometry with the smallest difference whatever the geometry or the pitch used. For small antennas, with a width w = 1.15 mm, the best antennas are those with a high contact in the meshing. The following step is to produce and confront theoretical results to practical results.

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