# Electronically reconfigurable parasitic antenna array for pattern selectivity

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**Abstract:** Antenna arrays are commonly used to achieve high gains and beam steering, but they require complex feeding networks. For applications demanding moderate antenna gains ($\simeq 6$ dB) and planar radiating structures, printed Yagi-Uda antennas can offer many advantages, but clearly, they cannot cover the whole azimuth plane. A symmetric structure made of two Yagi-Uda antennas with two active elements, a shared reflector and two directors of variable length is here presented and demonstrated to have switched beams that cover all the azimuth plane. By lengthening the physical lengths of the directors, they turn to act as reflectors: as a result, this antenna system has the ability to switch between broadside, bidirectional end-fire and two opposite end-fire patterns. The feeding is provided by a balanced parallel strip-slot line without the need for a balun section and thus reducing the overall size of the antenna. A modified design is also presented, obtained by adding a reflector board which allows for higher gains and focused radiation reconfigurability in the half-space. Simulated and measured results of both designs are reported showing good agreement. The antenna has a compact size, wideband characteristics and directive pattern reconfigurability.

## 1 Introduction

Phased arrays are conventionally used for applications requiring beam steering. Despite their robustness, phased arrays are known to have complicated feed networks comprising phase shifters, power attenuators, among others, and demanding the connection of external biasing power [1].

On the contrary, reconfigurable antennas used for a variety of applications, especially for WLANs where shifting the main beam among discrete angles can significantly improve the signal to noise ratio, can be a valid and effective alternative. Smart antennas usually rely on some kind of a switching mechanism, which can provide frequency, radiation, and pattern reconfigurability, or a combination of them [2–9]. A conventional way to design a reconfigurable antenna is to employ RF switches to connect various parts of the antenna. Among RF switches, PIN diodes and varactors are known to be faster and more compact than RF-MEMS. The switching speed of varactors and PIN diodes are in the order of nanoseconds [10–12]. PIN diodes also need less complicated biasing circuits, which is a key criterion for the selection and have a lower cost. Reconfigurable antennas using PIN diodes [6–9] have more dynamic reconfiguration ability.

Planar directive antennas having a reconfigurable pattern are required for compact transceivers used to cover selective areas. They can enhance the performance of a wireless system by decreasing interference and offering re-use of channels since they suppress unwanted emissions and/or interference in the required directions [13].

In the literature, different works on pattern-reconfigurable parasitic antenna arrays have been reported, especially based on Yagi-Uda geometry; in [14] the numerical model of a planar parasitic antenna array with a switching circuit that utilises PIN diodes in order to achieve beam steering capability has been presented: two different radiation patterns with the beam peak direction at opposite sides can be achieved by activating or deactivating PIN diode switches, but any other pattern configuration, nor details on the feeding mechanism was reported.

In [15] a printed dipole in antipodal configuration is exploited as the driven element of a Yagi-Uda antenna, surrounded on both sides by several parasitic elements whose length can be changed electronically; this antenna exhibits three different switching modes but requires an external feed line making unpractical the integration with a circuit board. In [16], a compact printed Yagi-Uda antenna is presented. It exploits meandered feeding line to switch the antenna pattern from broad-side to end-fire radiation, but it is not reconfigurable. In [17, 18] a microstrip-fed compact antenna is presented. It provides three different switching modes: the first results in an omnidirectional pattern, whereas the other two offer directive patterns, in two opposite directions. This antenna is designed for the 2.4 GHz use, it exhibits narrow band characteristics whereas is lost for some switching cases. Furthermore, the gain obtained in the directive modes is only around 3 dB. In [19] the driver of the proposed reconfigurable Yagi-Uda antenna is a wideband omnidirectional circular monopole. Six directors that are divided into two groups, located on the two opposite sides of the driver and used to direct two end-fire patterns with opposite directions. The reflectors are two grounds whose length can be adjusted through embedded PIN diodes. This design is complicated where six bias lines and six DC power or grounded nodes are used.

In this paper, a printed symmetrised Yagi-Uda antenna with a common reflector placed in-between the two radiators is presented. This novel design has an integrated feeding line which allows for impedance matching for four different switching cases. In this design, the active element is a two-element half-dipole, directly connected to an input parallel-stripline. Since the parallel-stripline is a balanced waveguide, the use of a balun is unnecessary.

Two PIN diodes are mounted on each director to achieve pattern reconfigurability. When the two PIN diodes on the director are activated (ON state), the physical length of the strip is increased thus forcing the reflector behaviour. This change in the functionality of the two director strips allows the antenna to achieve pattern reconfigurability. When all four switches are

activated (ON state), the antenna pattern is broadside with two main lobes perpendicular to the board of the antenna. When all four switches are in OFF state, the antenna has a bidirectional end-fire pattern. One-directional end-fire pattern results when one of the PIN diode pairs is in ON state and the other pair is set in OFF state.

To increase the gain and obtain pattern reconfigurability only in half of the azimuth plane, a modified design was obtained by adding a second board, with three printed reflecting strips, placed at about $\lambda_0/4$ distance.

Both designs guarantee impedance matching in the band of interest for Wi-Fi applications around 2.4 GHz for all switching cases. The details of the antenna design procedure and its radiation characteristics are described in the following sections.

## 2 Reconfigurable symmetrised Yagi-Uda antenna design

In this paper, a symmetrised Yagi-Uda antenna with two active elements, a common reflector, and two directors is considered. Two mirrored half-wavelength dipoles serve as active elements, as shown in Figs. 1a and b.

On one side of each active dipole, a metallic strip with electronically-controlled length is strategically placed to act either as a director or as a reflector at 2.4 GHz. Unlike well-known designs in [4, 8, 20], our proposed antenna has no ground plane and it is based on a differential input thus avoiding the need for a balun and in addition, its radiation patterns are perpendicular to the feed line. The overall size of the proposed prototype antenna is $0.48\lambda_0 \times 0.8\lambda_0$ (see Fig. 1a). The fabricated antenna is shown in Fig. 2 on a 1.52 mm thick Rogers TMM4 substrate having a relative permittivity $\varepsilon_r = 4.5$ and a loss tangent of 0.002. The antenna's active elements and parasitic strips are fabricated on the top layer of the substrate. The feeding line is a parallel stripline made on both sides of the substrate. A quarter-wavelength transformer, which is part of the feeding line and connects the 50 $\Omega$ parallel stripline to the active elements, allows good impedance matching in all operation states. The reflector extends from the bottom part of the feed line and is connected to the active elements using a via (Figs. 1a and b). The length of the reflector can be used to adjust the bandwidth of the antenna, as resulted from the parametric numerical analysis. This antenna is initially designed to operate as a bi-directional end-fire array, which is accomplished by having the two parasitic elements acting as directors.
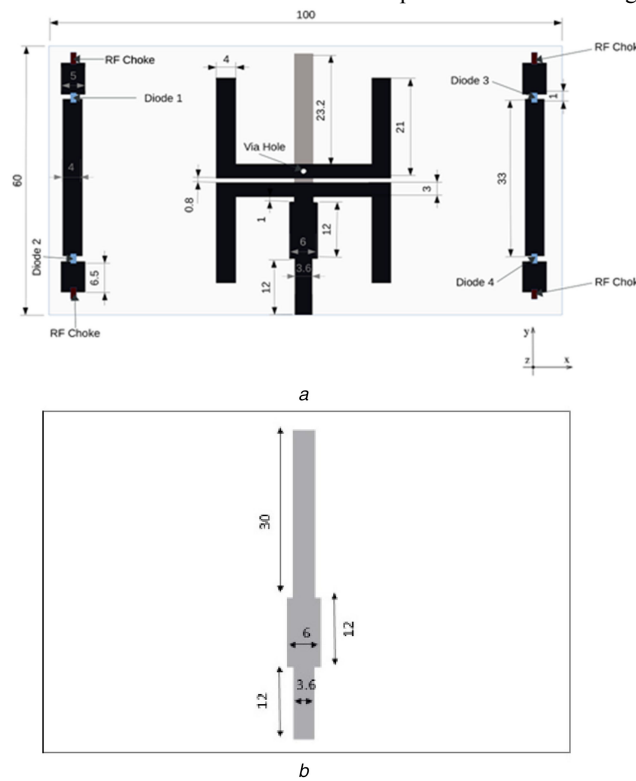


**Fig. 1** *Reconfigurable parasitic array (dimensions in mm)*
*(a)* Schematic diagram of the planar parasitic reconfigurable antenna; the dark area is on the top layer, whereas the light grey area refers to the reflector on the bottom layer, *(b)* Bottom layer of the antenna acts as a reflector
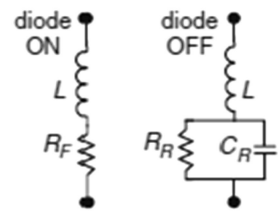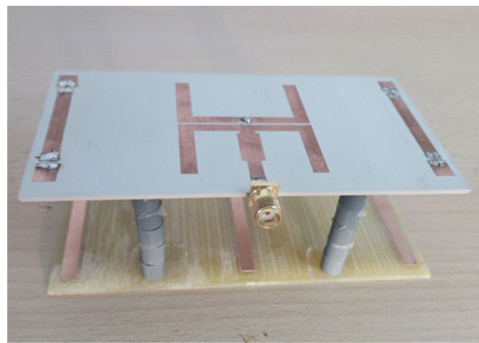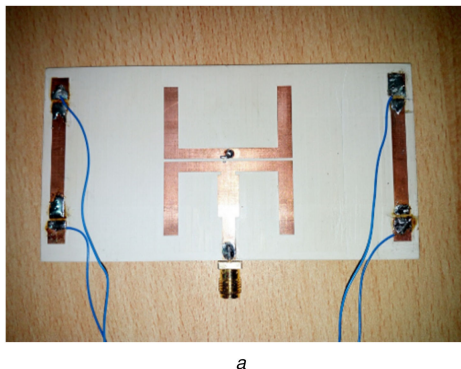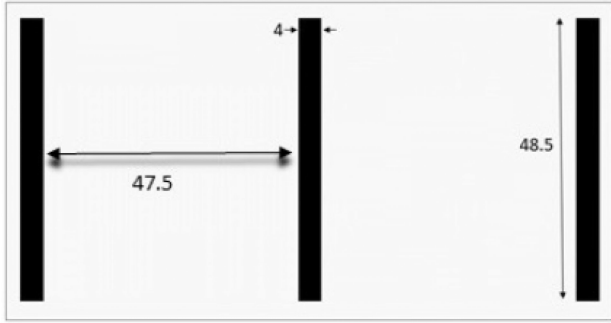


**Fig. 2** *Prototype of the proposed antenna*
*(a)* Top view, *(b)* Top view of the antenna with reflectors, *(c)* Equivalent circuit model of the PIN diode 'ON/OFF' configuration: $L = 0.5$ nH, $R_F = 0.8$ $\Omega$, $R_R = 1$ k$\Omega$, $C_R = 0.01$ pF

**Table 1** Four switching cases of interest

|  | Diode 1 | Diode 2 | Diode 3 | Diode 4 |
|---|---|---|---|---|
| Case_1 | OFF | OFF | OFF | OFF |
| Case_2 | ON | ON | ON | ON |
| Case_3 | ON | ON | OFF | OFF |
| Case_4 | OFF | OFF | ON | ON |



**Fig. 3** *Top view of the printed three reflectors*

Generally, in non-printed Yagi-Uda antennas, the separation between the driven element and the reflector is smaller than the spacing between the driven element and the nearest director ($0.25\lambda_0$ compared to $0.31\lambda_0$) [21]. For this design, the length of the reflector, its separation from the driven elements, as well as the distance between the driven elements and the parasitic strip lines were numerically found to achieve a good matching in all switching cases and to maintain the compactness of the antenna. In this case, the distance between the reflector and the driven element is about $0.13\lambda_0$ and between the driven element and the parasitic strip line is about $0.26\lambda_0$.

Beamforming is achieved by mounting two pairs of SMP1322 PIN diodes on each of parasitic strip lines. A two-branch DC bias network is required to apply a voltage to the PIN diodes and change their operating states. Four RF chokes are realised by four chip inductors placed on the board at the start of the DC bias wires. Fig. 2*a* shows the prototype photograph of the antenna and the DC wires connections.

The PIN diodes are modelled in HFSS using the lumped-element circuit shown in Fig. 2*c*.

Four switching cases are of interest and are listed in Table 1.

In Case_1, the two parasitic strip lines act as directors and both the two antennas behave as conventional Yagi-Uda radiators. As a result, the antenna system has a bi-directional end-fire pattern. The two main lobes occur in the $\theta = 90°$, $\Phi = -90°$ and the $\theta = 90°$, $\Phi = 90°$ directions.

In Case_2, the length of the two parasitic strip lines is increased and consequently, they start acting as reflectors. Thus, a broadside array having two main lobes normal to the board of the antenna is obtained (maximum radiation in the $\theta = 0°$, $\Phi = 0°$ direction and the $\theta = 180°$, $\Phi = 0°$ direction).

In Case_3 and Case_4, that are mirror versions of each other with respect to the $y–z$ plane. In Case_3, the left parasitic strip line acts as a reflector, while the right one acts as a director. The behaviour is very close to that one of a classic Yagi-Uda antenna, with a main end-fire pattern lobe in the $\theta = 90°$, $\Phi = 0°$ direction. The main lobe in Case_4 in is the $\theta = 90°$, $\Phi = 180°$ direction.

To restrict the radiation to only half of the azimuth plane and to obtain higher gains, a flat metal sheet can usually be used as a reflecting stage. However, for this purpose, three reflecting strip lines were printed on a second Rogers TMM4 board, which was placed about $\lambda_0/4$ below the antenna board, as shown in Fig. 3. Each reflecting strip line has a length of 48.5 mm and a width of 4 mm. Out of the four switching cases in Table 1, only three cases are of practical interest when the reflectors board is added. These are Case_2, Case_3 and Case_4. Case_2 results in a single main lobe perpendicular to the plane of the antenna ($\theta = 0°$, $\Phi = 0°$). With Case_3, the main lobe is tilted by 40° from the normal, that is



*a*



*b*
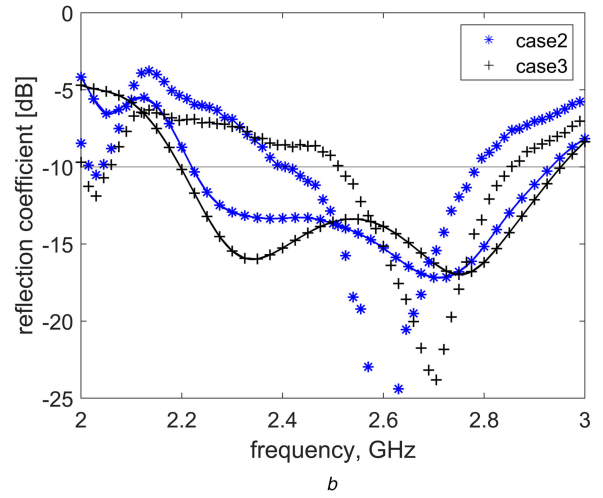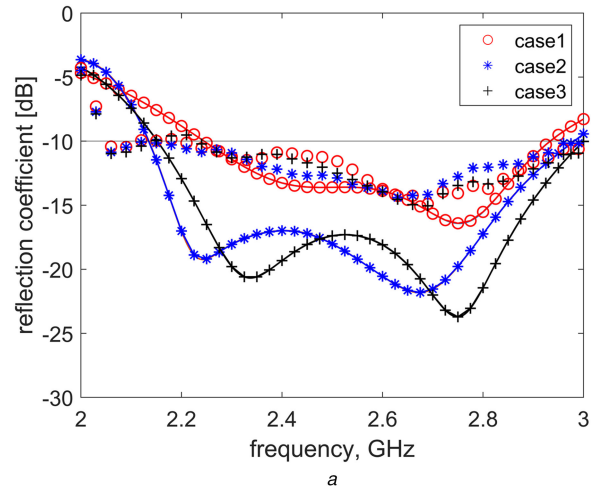
**Fig. 4** *Measured (dashed lines) and computed (solid lines) reflection coefficient*
*(a)* Antenna without reflector, *(b)* Antenna with reflector

it occurs in the $\theta = 40°$, $\Phi = 0°$ direction. In Case_4, the main lobe is in the $\theta = -40°$, $\Phi = 0°$ direction.

## 3 Measurement results and discussion

Figs. 2*a* and *b* show prototypes of the symmetrised, two-elements Yagi-Uda antenna, with and without the reflectors, after its fabrication and assembly. The prototype was fabricated on a 1.52 mm thick Roggers TMM4 substrate with relative permittivity of 4.5 and a loss tangent of 0.002. All the necessary components (connector, PIN diodes, RF chokes, DC pins) were soldered by hand.

The reflection coefficient for Case_1 (i.e. four unbiased diodes and the metallic strip lines physically disconnected from the small metallic strips), Case_2 (i.e. four biased diodes, and the metallic strip lines are physically connected with the small metallic strips), and Case_3 (two biased diodes and the others unbiased then two metallic strip lines are physically connected to the metallic strips) were measured in anechoic chamber using a two port Agilent N5230A network analyser; the prototype was fed with a coaxial cable. The metallic strip lines were connected to the small metallic strips via a surface-mount voltage controlled PIN diodes and two controls voltage ($+V = 1.4$ V) were placed on the conducting surface with RF chokes.

Fig. 4*a* shows the simulated and measured magnitude of the reflection coefficient ($S_{11}$) of the printed two-elements Yagi-Uda antenna for the three basic operating states Case_1, Case_2 and Case_3. Fig. 4*b* shows the magnitude of $S_{11}$ with the reflector board for Case_2 and Case_3. The Case_4 is not included in the plot since it is identical to Case_3 in both cases (due to the design symmetry).
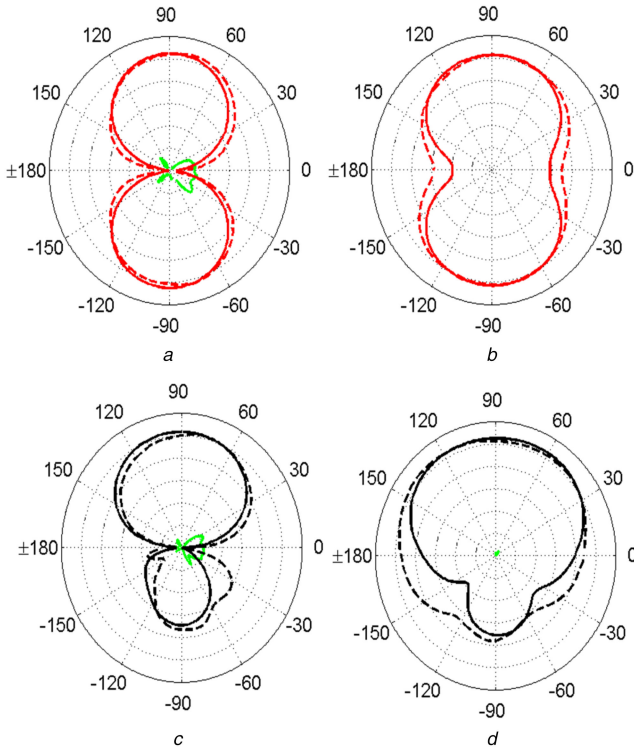
**Fig. 5** *Measured (dashed lines) and computed (solid lines) radiation patterns of the end-fire array. The green line shows the measured cross-polarisation component when higher than −20 dB. The display scale is from −20 to 10 dB (5 dB per division)*

*(a)* E-plane (Case_1): angles are measured starting from *x*-axis towards *y*-axis, *(b)* H-plane (Case_1): angles are measured starting from *x*-axis towards *z*-axis, *(c)* E-plane (Case_3): angles are measured starting from *x*-axis towards *y*-axis, *(d)* H-plane (Case_3): angles are measured starting from *x*-axis towards *z*-axis

Fig. 4*a* reveals a satisfactory impedance matching with a −10 dB fractional bandwidth higher than 26%. Some discrepancies are observed between simulated and measured results mostly due to fabrication and soldering inaccuracies. Also, the second antenna design with the exploitation of the reflector stage exhibits a good reflection coefficient with its magnitude below −10 dB level in both switching cases and in all the bands of interest for Wi-Fi applications.

The radiation patterns of Case_1 and Case_3 in the *E*-planes and *H*-planes are plotted in Fig. 5 at 2.44 GHz in the *x–y* and *x–z* planes, respectively: the measured diagrams exhibit a good agreement with HFSS simulations and confirm the symmetry with respect to the *y–z* plane in Case_1; there are two main lobes laying in the board plane in Case_1 (bi-directional end-fire pattern), the −3 dB beam-width is 68°, and one main lobe in Case_3 (end-fire pattern) with −3 dB beam-width equal to 86°. The Case_4 is not included in the measured plot since it is identical to Case_3 in both cases (due to the design symmetry). The measured (calculated) gain is 6.2 dB (6.68 dB) for the Case_1 and 5.1 dB (5.9 dB) for Case_3.

Figs. 6*a* and *b* show the patterns of the Case_2 at 2.44 GHz in the *x–z* and *y–z* planes and, as expected, is a broadside pattern with two main lobes perpendicular to the board. The measured (calculated) gain is 6.7 dB (7 dB) with the −3 dB beam-width equal to 83°. Figs. 6*c* and *d* show the radiation diagrams of the antenna with the reflecting board placed at about $\lambda_0/4$ below the antenna board for which we have three configurations: Case_2, Case_3 and Case_4; Case_2 exhibit one main lobe directed along the *z*-axis with the −3 dB beam-width equal to 65°, in the last two cases the main lobe is tilted of about 40° and the 3-dB beam width is 69°. The measured gain is around 8 dB for the three cases.

## 4 Conclusions

A symmetrised two-elements Yagi-Uda antenna made of two mirrored half-wavelength active dipoles, a common reflector and
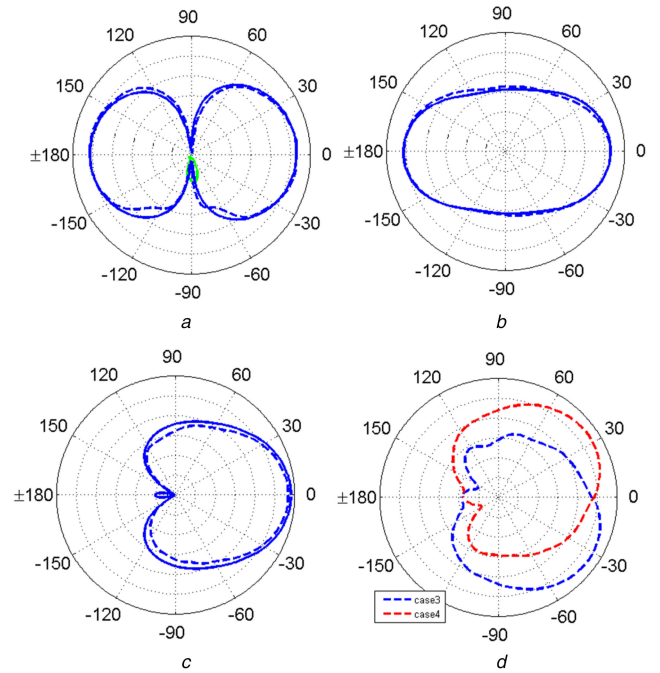


**Fig. 6** *Measured (dashed lines) and computed (solid lines) radiation patterns of the broadside array. The green line shows the measured cross-polarisation component when higher than −20 dB. The display scale is from −20 to 10 dB (5 dB per division)*

*(a)* E-plane (Case_2): angles are measured starting from *y*-axis towards *z*-axis, *(b)* H-plane (Case_2): angles are measured starting from *x*-axis towards *z*-axis, *(c)* H-plane (Case_2 with reflectors): angles are measured starting from *x*-axis towards *z*-axis, *(d)* H-plane (Case_3 and Case_4 with reflectors): angles are measured starting from *x*-axis towards *z*-axis

two metallic strips whose length can be electronically controlled, was designed, fabricated and tested. The proposed antenna operates in the WLAN band around 2.4 GHz. Two PIN diodes are mounted on each parasitic strip to obtain the pattern reconfigurability. The antenna demonstrates to have switched beams that cover all angles in the azimuth plane. The reflection coefficient and far-field patterns for various configurations were numerically calculated and experimentally measured showing good agreement. Despite the compact size ($0.48\lambda_0 \times 0.8\lambda_0$) broadband characteristics and gains of 6.2, 6.7 and 5.1 dB are achieved for the bi-directional end-fire (Case_1), broadside (Case_2) and the end-fire (Case_3) radiations. A modified design was obtained by exploiting the second board with three reflecting stripes properly placed on it allowing for higher gains and focused radiation reconfigurability in half of the azimuth plain.

The feeding realised with a parallel strip-line avoids the use of a balun section thus reducing remarkably the total size and allowing an easy integration with the electronic part of the circuit board.

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