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Transparent and miniature FM antenna in printed technology

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Research Paper

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Abstract

An optically transparent and electrically small frequency modulation (FM) radio receiving antenna has been designed and fabricated from a mesh silver layer printed onto a glass substrate. The studied FM antenna consists of a transparent meandering monopole associated with a micrometric size MEtal Semiconductor Field Effect transistor. An optical transparency of 87% and a sheet resistance lower than 0.22 Ω/sq are obtained. The received signal strength indicator and the signal-to-noise ratio are both measured and compared with those of a commercial monopole antenna (a quarter-wave wire antenna). The transparent FM antenna exhibits similar radiofrequency performance with, in addition, a low visual impact.

Introduction

The development of wireless communication increases the needs in miniaturized and integrated antennas. These miniaturization and integration are very useful for low-frequency applications (VHF/UHF bands) and for general public applications, such as frequency modulation (FM) radio reception on mobile phones and tablets. It induces a growing demand for small FM antennas. For mobile phones and tablets, antenna integration is required to replace the external antenna located in the headphone wires. For automotive applications, the FM antenna is most of the time placed on the top of the roof and is subject to urban damage and need mechanical placement (roof drilling that could add tightness problems). For these kinds of application, the development of optically transparent and electrically small antennas printed onto the glass (screen or automotive window) is completely relevant. That is the purpose of the present study.

Many passive designs have largely been investigated to get electrically small antennas such as meandering, helical, patch, dielectric resonator antennas, etc. [1]. These designs can be combined with materials [2,3] for a better integration into structural panels. They can also include passive and active components [4] to further improve size reduction or to add new functionalities, such as frequency tunability [5].

For this study, we select two complementary routes to fabricate an electrically small antenna: a meandering design associated with an active component. In addition, the antenna will be optically transparent for a better implementation on glazed surfaces such as car windows. The main difficulty in the fabrication of such antennas lies in the development of materials combining both a high electrical conductivity and a high level of optical transparency. Some materials meet the two criteria, such as those belonging to the transparent conducting oxide (TCO) family [3,6], TCO/metal multilayers [7–9], metal nanowires [10], and conductive polymers [11]. However, these solutions involve radiofrequency loss due to the sheet resistance of the layers higher than 1 Ω/sq (Table 1), which restricts the antenna performance and increases the power consumption. A solution has been specifically developed in the Laboratory for this kind of application: the micrometric mesh silver layer, which provides a high level of optical transparency with a low-sheet resistance value [12] (Table 1).

In this study, we present a small transparent FM receiving antenna. The printed meandering monopole antenna is designed to operate in the FM radio band (88–108 MHz). Miniaturization of the FM antenna is also improved by the use of a MESFET transistor (MEtal Semiconductor Field Effect Transistor). Optical transparency is achieved thanks to a transparent and conducting mesh silver layer printed ontoa glass substrate. This paper is organized as follows. The antenna design and fabrication are first detailed. Then numerical simulations are presented in the section "Numerical results and radiofrequency measurements". Measurements of the received signal strength indicator (RSSI) and of the signal-to-noise ratio (SNR) are also presented and compared with those of a commercial wire monopole antenna. Finally, the conclusion is drawn in the section"Conclusion".

Antenna design and fabrication

The structure of the studied active receiving antenna is inspired from [4] and depicted in Fig. 1. The antenna combines a meandering monopole with a MESFET transistor (ATF

Table 1. Electrical and optical performance of transparent and conducting materials

Materials	Sheet resistance (Ω/sq)	Optical transparency (%)
TCO [3,6]	10	80
Multilayers [7–9]	1–8	75–80
Nanowires [10]	3–10	80–90
Conductive polymers [11]	9.5	Not available
Micrometric mesh silver layer [12]	0.015–0.5	75–90

21100). The printed wire monopole antenna shows a quasi-omnidirectional radiation pattern, such as that of commercial FM antennas located on the vehicle roofs. The substrate used is a 101.6 mm × 101.6 mm × 0.7 mm 1737 Corning Glass with a dielectric permittivity $\epsilon_r = 5.7$, a loss tangent $\tan\delta = 0.006$ at 2 GHz and an optical transparency $T_{sub} = 92\%$ in the visible light spectrum (due to Fresnel loss). The wire length (295.4 mm) and its width (8 mm) comply with a quarter-wave monopole antenna design. The number of meanders has been selected here for printing the antenna onto a square area (each side measuring ~80 mm), thus locating the covered area. Furthermore, the reversal of the main current propagation direction in each successive meander restricts the cross-polarization in the H-plane (Fig. 1).

The MESFET transistor is used in common source configuration as an amplifier. The source is grounded through a parasitic printed line. The grid is linked to the monopole and the drain to the output of the antenna. The bias circuit is detailed in Fig. 2. C is a decoupling capacitor of 100 nF; $L1$ and $L2$ are choke inductors of 10 μH. The transistor is polarized under a drain voltage $V_{DS} = 3$ V and a drain current $I_{DS} = 20$ mA. The transistor has a micrometric size (outside dimensions: 380 μm × 480 μm), thereby a low visual impact on the global transparency of the antenna.

The transparent and conducting layer used to fabricate the printed FM antenna is a home-made micrometric mesh silver film. The pitch p and metal strip width s are selected to get a high level of optical transparency (equation 1), and to be no-visible to the naked eye. For this, the pitch of the mesh needs to be smaller than the human visual acuity: $\theta_{min} \approx 4.9 \times 10^{-4}$ rad [13] at the viewing distance d (equation 2). Therefore p has to be smaller than 400 μm at $d = 0.75$ m.

$$T(\%) = \left(\frac{p-s}{p}\right)^2 \times T_{sub}, \quad (1)$$

$$p < d \times \theta_{min}. \quad (2)$$

The selected parameters are $p \approx 360\mu$m and $s = 10\ \mu$m, given a theoretical optical transparency $T = 87\%$ (including Fresnel loss). Moreover, the sheet resistance R_s' of the mesh metal layer is computed from equation 3 as follows:

$$R_s' = \frac{p}{s} \times R_s = \frac{p}{s} \times \frac{\rho}{t}, \quad (3)$$

where R_s is the sheet resistance of the metal layer before the mesh processing, ρ is the resistivity ($\rho = 1.64 \times 10^{-8}\Omega$.m for silver [14]) and t is the thickness of the metal layer ($t = 6\ \mu$m). With the selected parameters, $R_s' = 0.10\ \Omega$/sq which is significantly lower than that of the available commercial solution AgHT-4 (4 Ω/sq [15]) or from an OTC/metal multilayer solution (4.99 Ω/sq [7]).

The mesh silver film was fabricated with the process fully described elsewhere [12]. A continuous silver film (6 μm-thick) and a titanium underlayer (5 nm-thick) are both deposited onto 1737 Corning glass substrate by RF magnetron sputtering technique at room temperature. The titanium underlayer is used here only to ensure the strong adhesion of the silver overlayer onto the glass substrate. Subsequently, a standard photolithographic wet etching process is used to fabricate the transparent sample from a mesh photomask. Stripping of the photoresist leaves the antenna pattern with a periodic array of apertures in the metal coating (Fig. 3). A detail of the mesh pattern is shown in Fig. 4.

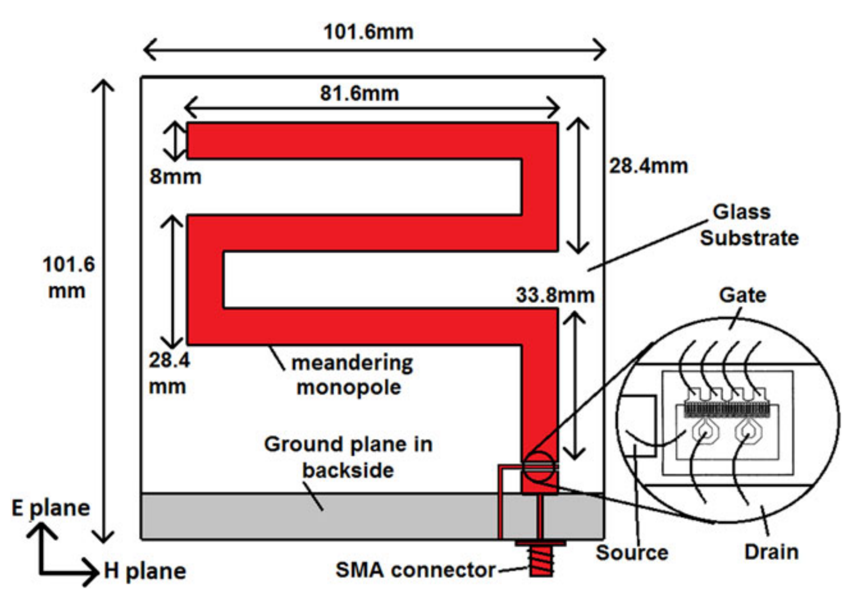

Fig. 1. Geometry and dimensions of the meandering active antenna.

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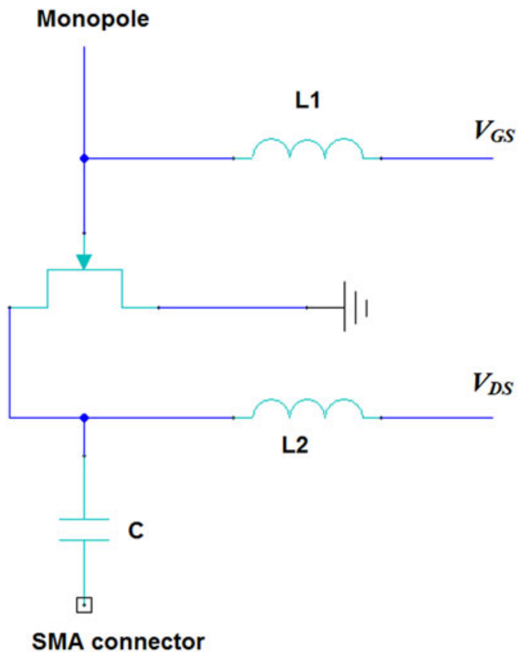

Fig. 2. Detail of the bias circuit.

The thickness of the silver layer remains small ($t = 6\,\mu$m) compared with the skin thickness value $\delta = 6.4\,\mu$m (equation 4) at the operating frequency f (~100 MHz):

$$\delta = \sqrt{\frac{\rho}{\mu_0 \pi f}}, \tag{4}$$

where μ_0 is the permeability of the free space.

To avoid the loss due to skin depth effect, it is recommended to use a metal thickness greater than $3 \times \delta \approx 19\,\mu$m. Nevertheless, the deposition technique used here does not allow access such a thickness, explaining the choice of a $6\,\mu$m-thick silver film. It is worth noting that the skin depth effect is also present in the width of the strips due to their narrowness ($s = 10\,\mu$m). This constraint did not appear in the previous studies based on the transparent micrometric mesh antennas due to the higher operating frequencies (865 MHz [16], 2 GHz [17], 10 GHz [5], 24 GHz [18], 60 GHz [19]). It would be possible to solve this deficiency by doubling the strip width ($s = 20\,\mu$m) but at the expense of the sample optical transparency (theoretical variation from 87 to 82%). In the present study, we have favored the high-optical transparency level of the printed FM antenna.

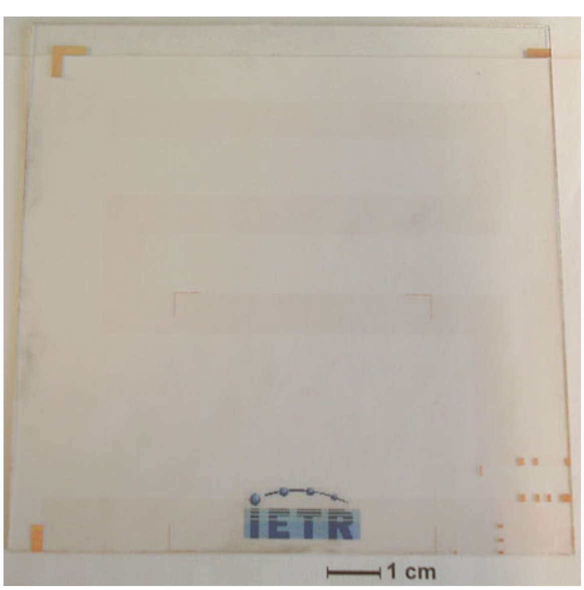

Fig. 3. Picture of the transparent FM antenna placed above the laboratory logo.

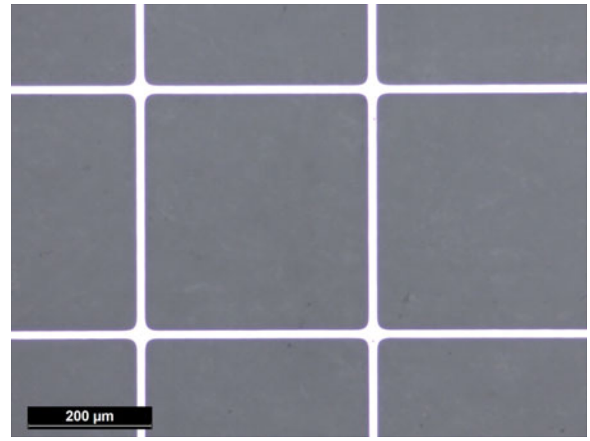

Fig. 4. Optical microscopy observation of the mesh pattern.

The optical transparency of the antenna was measured by a UV/visible spectrophotometer. The measured transparency remains constant ($T = 87\%$) over the entire visible light spectrum (Fig. 5), in complete agreement with the theoretical value ($T = 87\%$). No interference fringe is observed on the curve, as it can be noticed with OTC single layers [8] or OTC/metal multilayers [7]. The sheet resistance was measured with a standard four-probe setup with a current source and a high-impedance microvoltmeter. The measured value is $R'_s = 0.22\ \Omega$/sq, higher than expected ($R'_s = 0.10\ \Omega$/sq, see equation 3). The higher experimental value may be due to the small width of the antenna ribbon (8 mm, see Fig. 1) which restricts the roll-out of the current during the measurement, and thereby artificially increases R'_s value.

Numerical results and radiofrequency measurements

A model of the MESFET transistor was used with ADS software (Fig. 6). S parameters of the transistor (Fig. 7) were thus retrieved

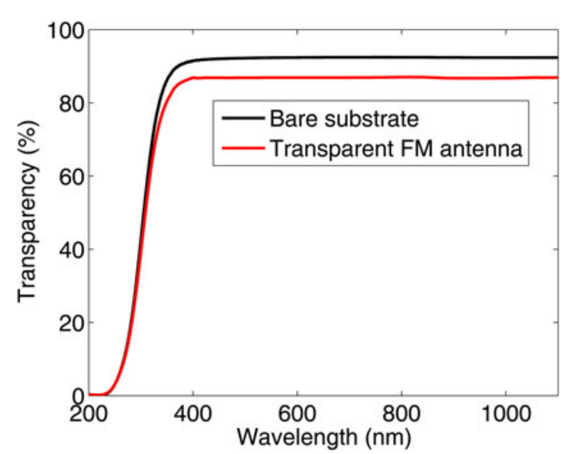

Fig. 5. Measured optical transparency.

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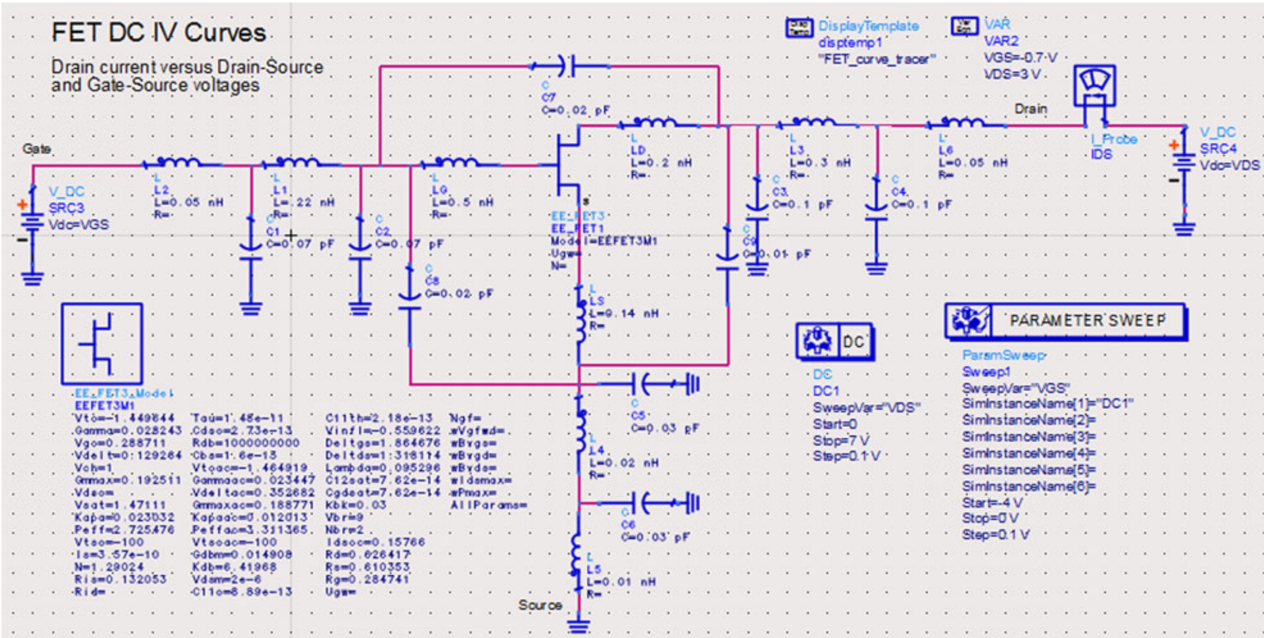

Fig. 6. ADS model of the MESFET transistor.

under biasing values indicated in the section "Antenna design and fabrication" ($V_{DS} = 3$ V and $I_{DS} = 20$ mA).

Due to the unilaterally of the transistor, the antenna only operates in reception. To evaluate its input impedance, an electromagnetic calculation was combined with the electrical model of the transistor. The numerical simulations were performed with CST Microwave Studio®. The simulated FM antenna was not designed with the mesh silver layer (due to the very high numerical capabilities required) but with a continuous 6 μm-thick silver layer printed onto the 1737 Corning glass substrate. Figure 8 presents the simulated reflection and transmission coefficients magnitudes of the FM receiving antenna. Its dimensions have been optimized to set the resonance frequency close to 100 MHz. The reflection coefficient is above −10 dB over the entire FM radio band (88 − 108 MHz) through the MESFET transistor direct matching. Indeed, the antenna input impedance without the transistor is equal to 1−j251 Ω at 100 MHz. Due to the unilaterally of the transistor, the input impedance of the active antenna is equal to the output impedance of the transistor itself (94−j4 Ω at 100 MHz). Therefore, the monopole antenna does not require any additional impedance matching adapter, contributing to its miniaturization. It is worth noting that the MESFET transistor also amplifies the received FM signal with low power consumption.

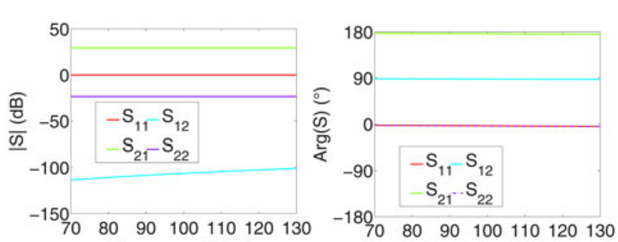

Fig. 7. *S* parameters of the MESFET transistor (port 1: gate-source and port 2: drain-source).

To assess the gain of the antenna, the Link Budget Method described in [20] is used with the Friis formula expressed as follows:

$$G_{ant(dB)} = S_{21(dB)} - 20\log\left(\frac{\lambda}{4\pi D}\right) - G_{Tr(dB)}, \tag{5}$$

where $G_{ant(dB)}$ is the gain of the FM receiving antenna, $S_{21(dB)}$ is the transmission coefficient, $G_{Tr(dB)}$ is the gain of the transmitting antenna, D is the distance between the transmitting and receiving antennas in far-field conditions and λ is the working wavelength. The transmission coefficient simulated at 100 MHz with $D = 1.7$ m and $G_{Tr} = 2.2$ dBi is equal to $|S_{21}| = -28.7$ dB, yielding a FM antenna gain $G_{ant} = -13.8$ dBi. This low value is due to the small electrical dimension of the FM antenna ($\lambda_0/21$ at 100 MHz) and the skin depth effect. Nevertheless, this gain is valuable for a FM radio reception application and is higher

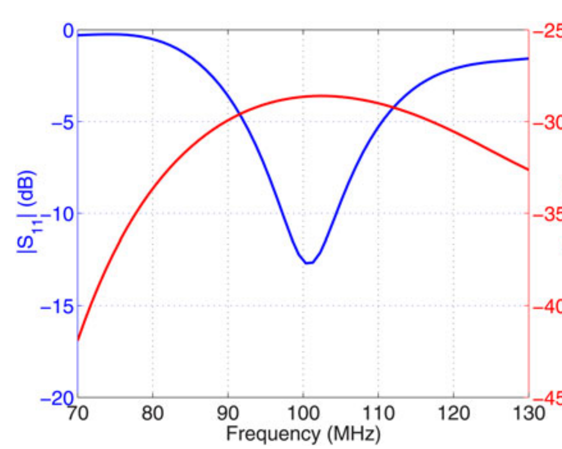

Fig. 8. Reflection $|S_{11}|$ and transmission $|S_{21}|$ coefficients computed with CST software.

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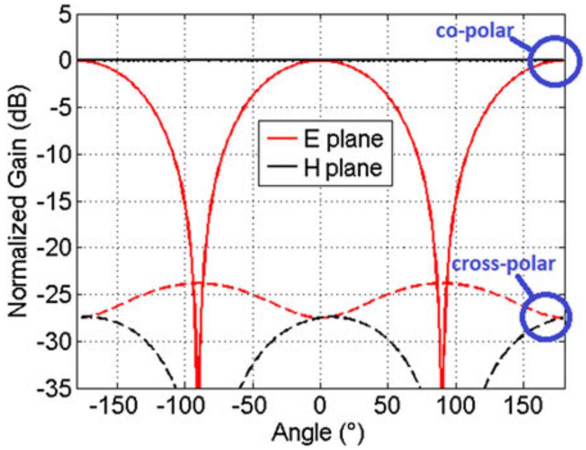

Fig. 9. Normalized simulated radiation pattern of the passive antenna (without the MESFET transistor).

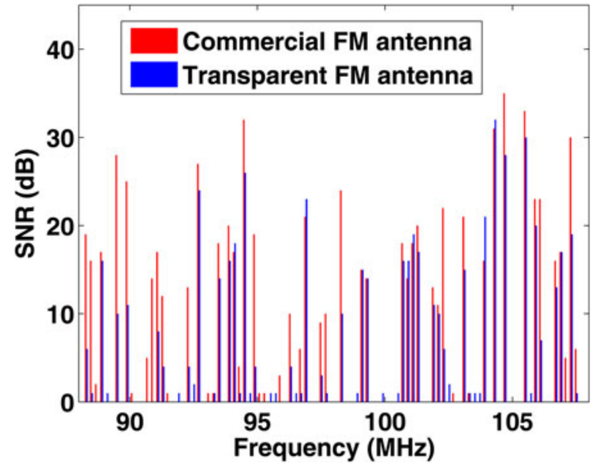

Fig. 11. Measured SNR.

than that reported in [4] (−19.6 dBi) because of its relative larger size ($\lambda_0/21$ in our case against $\lambda_0/175$ in [4]).

The FM antenna operating in the receiving mode, the radiation pattern was simulated without the active MESFET transistor (Fig. 9). It is similar to that of a dipole antenna: omnidirectional in the *H*-plane and a 90° half power beam width in the *E*-plane. As expected, the cross-polarization value remains lower than −20 dB.

The RSSI (Fig. 10) and the SNR (Fig. 11) were measured and compared with those of a commercial monopole antenna (a quarter-wave wire antenna). The average difference in RSSI between the transparent FM and the commercial antennas is 8.8 dB, and only 4.4 dB for the SNR parameter. These ensure a valuable received signal quality to listen to the FM radio without interferences (hiss, crackle, and fade). From the RSSI measurement, it is possible to assess the gain of the transparent FM antenna from the gain of the commercial monopole antenna (1 dBi). The transparent FM antenna gain is therefore estimated at about −8 dBi, value higher than that obtained from the simulated result (−13.8 dBi). We assign this result to the measurement environment (multipath reception of the FM signal). It is also possible to compare the performance of the present antenna to another electrically small ones (Table 2). It is worth noting that

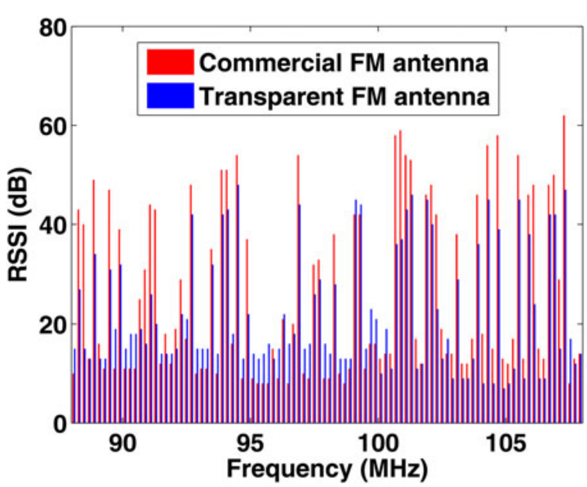

Fig. 10. Measured RSSI.

Table 2. Dimensions and performance of different electrically small FM antennas

FM antennas	Dimensions (mm × mm)	Gain (dBi)	Optically transparent
Anguera *et al.* [21]	130 × 75	−19	No
Liu *et al.* [22]	40 × 15	−32	No
Loutridis *et al.* [23]	50 × 33	−25	No
Taachouche *et al.* [4]	50 × 50	−20	No
Present work	100 × 100	−8	Yes

the FM antennas available in the literature are not optically transparent, thereby strengthening our technology.

Conclusion

An optically transparent FM antenna with a small electrical dimension ($\lambda_0/21$) has been designed, fabricated, and characterized. This antenna exhibits a high level of transparency (T = 87%) over the entire visible light spectrum with a low-visual impact, unlike the available see-through FM antennas "http://www.max-signal.com/product/12/monarch-50-hdtv-indoor-antenna-transparent". The sheet resistance value remains lower than 0.22 Ω/sq. A gain close to −8 dBi at 100 MHz associated with radio performance (RSSI and SNR) similar to that of a commercial quarter-wave wire antenna have been obtained. These results allow us to consider its further implementation onto automotive glazing for a high-quality FM radio reception.

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Mohamed Himdi received the Ph.D. degree in signal processing and telecommunications from the University of Rennes 1, France in 1990. Since 2003, he has been a Professor with the University of Rennes 1, and the Head of the High Frequency and Antenna Department until 2013, of IETR. He has authored or coauthored 107 journal papers and over 240 papers in conference proceedings. He has also coauthored nine book chapters. He holds 35 patents. His research activities concern passive and active millimeter-wave antennas. His research also include development of new architectures of antenna arrays, and new three-dimensional (3D) antenna technologies. He was Laureat of the 2d National Competition for the Creation of Enterprises in Innovative Technologies in 2000 (Ministry of Industry and Education). In March 2015 he received the JEC-AWARD at Paris on Pure composite material antenna embedded into a motorhome roof for the Digital Terrestrial Television reception.