Flexible and Semi-Transparent Antenna for ISM Band Fabricated by Direct Laser Writing

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In this paper, a flexible and semi-transparent antenna is proposed having impedance bandwidth of 110 MHz (from 2.45 GHz to 2.56 GHz) of ISM band which covers the most popular (2.4 GHz) for Wi-Fi application all over the world. A simple dipole shape rectangular ring antenna with two extended edge on the opposite sides was prepared by laser direct writing on an Au sputtered PET film. The center part of the antenna was kept empty and transparent intentionally to incorporate with either a planar capacitor for microwave wireless charging or to integrate this antenna with a solar cell in future. The compact, miniature and flexibility of the antenna are suitable for easy integration in any smart devices or clothing for wireless charging to implement self-powered sensors. The performance of the patch antenna is evaluated using return loss (S11) parameter analysis. A measured reflection coefficient and simulated current distribution along with radiation pattern demonstrate that the fabricated antenna is suitable for Wi-Fi application.

Keywords: Flexible, Semi-transparent, Direct Laser writing, Wi-Fi

1. Introduction

Flexible electronics describe circuits that can bend and stretch, enabling significant versatility in applications and the prospect of low-cost manufacturing processes. A flexible substrate should be mechanically robust with highly deformability and extreme tolerance levels of bending repeatability to adapt with flexible technologies and integrated components. Flexible electronics have been extensively studied because they provide a simple means of integrating electronic devices on curved surfaces for various applications, such as wearable devices, artificial skins, flexible displays, and flexible solar energy harvesters [1]. All of these reconfigurable antennas are mainly focused on frequency tuning and exhibit their radiation patterns with relatively low directivity. Moreover, the flexible antennas have over-performance compared to rigid devices, in terms of compactness, flexibility, durability, lightweight, and energy efficiency. However, the antenna designers working on flexible antennas must address some challenges, including the shift of the resonant frequency and degradation impedance mismatch due to the variation of effective capacitance during bending of the antenna. Other than the reconfiguration and flexibility characteristics, the antenna compactness is highly appreciated as the miniaturized antennas significantly reduce the size of electronic systems [2]. Furthermore, optically transparent antennas have attracted a great deal of interest in the recent years due to the potential applications in solar panels integrated with satellites, smart windows and other related areas [3]. However, the realization of flexible and optically transparent patch antennas is very challenging due to the unavailability of suitable materials and complex fabrication processes.

In the traditional transparent thin films [4] and meshed conductors [5], there is a tradeoff between the optical and electrical properties, hence, high
optical transparency and good RF performance cannot be achieved simultaneously. Moreover, complex and costly fabrication techniques are required to fabricate antennas with these materials. It is also challenging to maintain robust integration of these transparent conductors with flexible substrates in harsh physical deformations [6].

In near future, all the devices will be interconnected that linked with an internet itself. Smart energy distribution, health care, smart cities and smart car supposed to exchange information in forthcoming years through internet access. In massive IoT applications, consistent wireless connectivity between sensor and cloud is prerequisite with the cost of sufficient low power. Radio frequency (RF) band for GSM, 3G, LTE, and Wi-Fi with frequencies between 900 MHz and 2.6 GHz are considered as one of the potential and optimistic sources in urban environment due to their greatest amount of ambient energy. However, there is a need for low-cost and eco-friendly antenna materials that are flexible and/or optically transparent to fully embody the ubiquitous potential of IoT [7]. Flexible wireless sensors could be integrated as wearables in clothing [8] or directly on the human body to monitor, for instance, the temperature, blood pressure and heart rate of patients on a continuous basis [9].

The innovation of sensor manufacturing process both in material and fabrication technique is necessary to reduce the cost of them. The printed electronics is one of the candidates for the innovative manufacturing. The contribution of laser processing in printed electronics is expected because of the compatibility with on-demand manufacturing and role-to-role processing [10]. A number of printing and lithographic techniques have been used for the preparation of in plane patch antenna, but further improvements in cost, fabrication time, scalability, and compatibility to the current electronic industry are required to exert their full potential and commercialization. Laser direct writing is a noncontact, fast, single-step fabrication technique with no need for masks, post processing, and a complex clean room, and compatible with current electronic product lines for commercial use. Thus, it has potential to be employed in the fabrication of materials with specific patterns and even preparation of self-powered integrated stretchable devices [11]. The advantages of the laser direct writing are the high resolution up to sub-micron level and the fast sintering process where the local heating at a small laser beam focal point reduces the damage of a polymer substrate in flexible device manufacturing [12]. In this paper a compact, flexible and semi-transparent antenna for (Industrial, Scientific and Medical) ISM band that achieves a stable impedance bandwidth even after 5 mm bending diameter has been designed and investigated. The planar antenna consists of a simple rectangular ring structure with extended length at opposite direction. The antenna structure is flat and its design is simple and straightforward.

Fig. 1. Dimension in mm of the proposed antenna.

2. Material Preparation and Antenna Design

Figure 1 shows the geometrical layout of the proposed laser-written antenna pattern, which consists of a simple dipole shape rectangular ring. The patch, which has a compact dimension of 40×22 mm, is prepared in an inexpensive (polyethylene terephthalate) PET substrate of relative permittivity 2.1, loss tangent 0.003 and thickness 0.5 mm, which is a special PET film designed for monochrome laser printing (A-ONE 27054). The surface roughness of the PET film improved the adhesion between Au layer and PET substrate. Thin substrates with lower dielectric constants are desirable for good antenna performance because they minimize undesired radiation and coupling and provide better efficiency and larger bandwidth, respectively [13]. The performance of the antenna has been analyzed by AXIEM 3D planar method-of-moments (MoM) EM analysis simulator by Cadence. The proposed antenna is designed to operate at 2.45 GHz to 2.56 GHz to cover the Wi-Fi band. At first deep UV treatment using a UV/ozone surface processor equipped with a low-pressure Hg lamp (PL-16, SEN LIGHTS Co., Ltd.) was carried out for 10 minutes followed by Au sputtering of 120 nm thickness by JFC-1500 ion sputtering device. Finally, an antenna pattern was drawn by laser
ablation using a galvano-scanning of the laser beam controlled with a laser marking software (BjJcZ, EzCAD). The laser source was an ns fiber laser (Raycus, RFL-P30Q, 1064 nm, 34 W, pulse width 125 ns, 30-60 kHz). The laser beam was scanned by a galvano-scanner through an f-θ lens with the focus length of 100 mm. The return loss spectra were observed by a Tektronix TTR506A vector network analyzer for both flat and bending condition from 55 mm to 5 mm bending diameter. The transparency of the realized antenna was measured by spectrophotometer by Jasco V-670, within the wavelength from 300 to 1100 nm.

3. Simulation and Experimental Results

The semi-transparent antenna was subsequently fabricated for experimental verification, as shown in Figure 2a and 2b. The variation of the optical transparency of the fabricated antenna exhibits in figure 3. The transparency is about 87.7% for the PET before Au sputtering at 500 nm wavelength. The transparency drops to 67.5% and 34% in the center of the rectangular ring structure and on Au layer of the antenna respectively as predicted. Figure 4 illustrates the plots of the reflection coefficient (S11) for both simulation and measurement of the proposed antenna. It is observed from the plot that the prototyped antenna achieved a good impedance matching from 2.45 to 2.56 GHz with a measured|S11| parameter below -10dB. The return loss was reduced to a highest value of 15.45 dB and 35 dB for the simulation and measured results, respectively. The simulation and measured operating bandwidth of the proposed antenna were found to be 90 MHz and 110 MHz respectively with resonant frequency at 2.49 GHz which covers the entire Wi-Fi frequencies as mentioned earlier. A small deviation was observed because of the fabrication tolerance.

![Fig. 4. Simulation and measured reflection coefficient](image)

![Fig. 5. Bending measurement process](image)

The material exhibits remarkable flexibility and robustness, consequently, without any mechanical damage the antenna can be bent until 5 mm bending diameter as shown in Figure 5. The reflection coefficient against the frequency for the antenna bending from 55 mm to 5 mm were illustrated in Figure 6. Such bending experiments were carried out from the practical interest to
The presented antenna achieves a wider frequency range because the surface current maintains a harmonic order flow. From Figure 8 we can observe the simulated 3D radiation pattern of the proposed antenna. Figure 8a and 8b depicted an omnidirectional and donut shape radiation pattern for E-Phi and E-Theta respectively. Figure 9a and 9b demonstrate the top and bottom of the total radiation pattern. A considerable amount of back lobe has also been observed.

4. Conclusion
In this paper, a flexible and semi-transparent antenna is presented for Wi-Fi antenna application. Experimental results demonstrate that, the fabricated antenna could achieve an impedance bandwidth from 2.45 GHz to 2.56 GHz both in flat and 5 mm bending diameter status. The design of the proposed antenna is simple, easy to fabricate and will be compatible for any flexible electronic devices.

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References
1. W. Li, A. Meredov, K. Klionovski, and A. Shamim, 2019 IEEE Indian Conference on Antennas and Propogation (InCAP), Ahmedabad, India, (2019) 1.
2. N. Hussain, W.A. Awan, S.I. Naqvi, A. Ghaffar, A. Zaidi, S.A. Naqvi, A. Ifthikhar, and X.J. Li, IEEE Access, 8, (2020) 173298.
3. H. A. E. Elobaid, S. K. A. Rahim, M. Himdi, X. Castel, and M. A. Kasgari, IEEE Antennas and Wireless Propagation Letters, 16 (2017) 1336.
4. S. Y. Lee, M. Choo, S. Jung, and W. Hong, Appl. Sci., 8 (2018) 901.
5. T. Jang, C. Zhang, H. Youn, J. Zhou, and L. J. Guo, IEEE Trans. Antennas Propag., 65 (2017)
Fig. 6. Measured reflection coefficient for different bending diameter demonstrate the flexibility of this antenna. From the figure it was observed that for all the cases the variation of the antenna resonance frequency was only 2 MHz but with constant impedance bandwidth.

The simulated surface current distributions of the proposed antenna at resonance frequency of 2.49 GHz are illustrated in Figure 7. It is seen that, the strongest currents are concentrated on the right wing and the upper left side of the patch antenna and play a key role in creating resonance and omnidirectional radiation pattern.

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Fig. 9. (a) Simulated 3D radiation pattern from top view (b) Simulated 3D radiation pattern from bottom view

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2. N. Hussain, W.A. Awan, S.I. Naqvi, A. Ghaffar, A. Zaidi, S.A. Naqvi, A. Iftikhar, and X.J. Li, IEEE Access, 8, (2020) 173298.
3. H. A. E. Elobaid, S. K. A. Rahim, M. Himdi, X. Castel, and M. A. Kasgari, IEEE Antennas and Wireless Propagation Letters, 16 (2017) 1336.
4. S. Y. Lee, M. Choo, S. Jung, and W. Hong, Appl. Sci., 8 (2018) 901.
5. T. Jang, C. Zhang, H. Youn, J. Zhou, and L. J. Guo, IEEE Trans. Antennas Propag., 65 (2017) 50.
6. A. S. M. Sayem, D. Le, R.B.V.B. Simor, T. Bjorninen, K.P. Esselle, R.M. Hashmi, and M. Zhadobov, IEEE Antennas and Wireless Propagation Letters, 19 (2020) 2334.
7. M. A. Andersson, A. Özçelikkale, M. Johansson, U. Engström, A. Vorobiev, and J. Stake, IEEE Access, 4 (2016) 5850.
8. M. M. Ur Rashid, A. Rahman, L. C. Paul, and A. Krishno Sarkar, 2019 1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT), Dhaka, Bangladesh, (2019) 1.
9. S. M. R. Islam, D. Kwak, M. H. Kabir, M. Hossain, and K.-S. Kwak, IEEE Access, 3 (2015) 678.
10. A. Watanabe, A. Rahman, J. Cai, and M. Aminuzzaman, J. Photopolym. Sci. Technol, 33 (2020) 2.
11. A. Watanabe, A. Rahman, J. Cai, and M. Aminuzzaman, Proc. SPIE, 11674 (2021) 116740T.
12. A. Watanabe, A. Rahman, J. Cai, and M. Aminuzzaman, Proc. SPIE, 11268 (2020) 1126817.
13. A. Rahman, M.T. Islam, M. Samsuzzaman, M.J. Singh, and M. Akhtaruuzzaman, Materials, 9 (2016) 5.