Double slot aerosol jet printed antenna for X-band applications

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Abstract. A double slot antenna for X-band applications was designed and aerosol jet printing technology was used to fabricate the prototype with silver nano-ink on a flexible polyimide substrate. We investigated the microwave losses of printed antennas in the range from 100 kHz to 27 GHz, obtained at sintering temperatures of 200 °C and 250 °C. Double slot X-band antennas have been calculated and measured. It was found that an operating bandwidth of the printed antenna is 10% in the region of the central frequency of 10.5 GHz. Thus, the possibility of forming antennas on flexible polymer substrates with high functional characteristics by aerosol jet printing method has been demonstrated.

1. Introduction
The currently developing printed electronics is attractive not only for the low cost of printing and simplicity of prototyping, but also for the possibility of creating flexible electronic circuits and devices [1–3]. Among the existing printing methods, aerosol jet printing is the most promising technology, since it allows the formation of functional elements with a minimum lateral size of up to 10 microns on different types of substrates, including flexible polymer substrates [4,5]. The aerosol jet printing method is in demand for various fields of application, including the manufacture of transistors, sensors, solar cells, microheaters, microwave structures and interconnections [6–9].

Flexible planar microwave structures are in demand for creating conformal low-profile antennas and quasi-optical filters based on frequency selective surfaces that can be placed on curved aerodynamic surfaces of ground vehicles and aircraft. Fiberglass hulls and keels of unmanned aerial vehicles (UAVs) allow placing antennas on their bearing surfaces without using the ground plane, made in one metal layer. Antennas such as the double slot [10,11], are based on high-impedance transmission lines and, unlike patch antennas, have high antenna efficiency. Single flexible antennas can be combined into conformal antenna arrays that cover large areas on the UAV body and have a high collective gain. We optimized the printing parameters for silver ink on polyimide substrate and printed several samples of the X-band double slot antenna. This range can be used not only for high-speed communication channels, but also for airborne radars and proximity sensors.

2. Experimental
A double slot antenna in the form of a silver film of a given geometry was fabricated by focused deposition of aerosol microdroplets from silver nano-ink onto a polyimide substrate by pneumatic method using an AJ 15XE aerosol jet printer (Neotech AMT GmbH). The nano-ink was a mixture of
silver nano-ink PG-007 (Paru Co. Ltd.) based on solvents 1-methoxy-2-propanol (MOP) and ethylene glycol (EG) in a volume ratio of 3:1, respectively [12]. Pure nitrogen N₂ (99.9999%) was used as a carrier gas. A nozzle with an outlet diameter of 300 μm was used to form the antenna. The antenna was formed at the values of aerosol and sheath flow rates, and printing speed equal to 50 sccm, 80 sccm, and 500 mm/min, respectively. After deposition, a silver film was sintered at temperatures of 200 °C and 250 °C for 60 min to form a conductive structure.

The design of the double slot antenna is presented in figure 1. Antenna geometry is designed and optimized for 10.5 GHz using high frequency simulation software (HFSS). The antenna is designed on a flexible polyimide dielectric substrate 120 μm thick and dielectric constant ε = 3.5. The antenna was a silver film 20x20 mm² in size and has thickness about 4 μm. Two narrow 0.1 mm holes in the form of rectangular slots were made in the silver film. Functionally, the antenna consisted of two magnetic dipoles formed by half-wave λ/2 resonators based on a slot line. The dipoles are also located at a distance of λ/2 and are interconnected by a coplanar line in the center of which is the power point.

The vector analyzer (Keysight N5242A-200) was used to measure the return loss, S11-parameter, of antennas sintered at 200 °C and 250 °C. Microstrip transmission lines with a characteristic impedance of 50 Ohm were investigated to study microwave losses in deposited silver films in a wide frequency range. In such lines, the current density in the conducting layers has maximum values. Two silver electrodes with a width of 10 mm and 0.38 mm were printed on opposite sides of flexible substrate. SMA connectors were soldered at the ends of the 10 cm long microstrip transmission lines section, see figure 2. The morphology of printed antennas was investigated using a scanning electron microscope (SEM) (JSM-7001F, JEOL Ltd.)

![Figure 1. The design of the double slot antenna](image1)

**Figure 1.** The design of the double slot antenna \((L_g = 20 \text{ mm, } L_s = 11 \text{ mm, } W_s = 0.1 \text{ mm, } W_b = 0.4 \text{ mm, } S = 8.4 \text{ mm, } a = 1.2 \text{ mm, } b = 1.8 \text{ mm}).**

![Figure 2. Aerosol jet printed microstrip transmission line on flexible polyimide substrate](image2)

**Figure 2.** Aerosol jet printed microstrip transmission line on flexible polyimide substrate.

3. **Results and discussion**

The vector analyzer was used to measure the transmission coefficient S21 through the printed microstrip transmission line in the range from 100 kHz to 26.5 GHz. The measurement results for Ag
films with sintering temperatures of 200 °C and 250 °C are presented in figure 3a. The curves show equidistant resonance dips, which are present due to non-optimal contact at the place where the microstrip transmission line is soldered to the coaxial connector. A numerical model of the microstrip transmission line with losses was created, in which the frequency-dependent resistance per square (Ohm sq⁻¹) of the area of the silver films was set. Comparison of the results of numerical simulation by the FDTD method with the experimental curves S21 allows one to obtain the frequency dependence of resistance, see figure 3b. It can be seen that up to 15 GHz the resistance of Ag films with sintering temperature of 200 °C is higher than that for Ag films with temperature of 250 °C. This could be explained by the fact that at higher temperatures printed films have less binding agent and silver nanoparticles has better contact to each other. At frequencies above 15 GHz, the capacitance of the gap between nanoparticles makes a significant contribution to the conductivity. Therefore, the values of resistance are the same for Ag films with different sintering temperatures.

Figure 3. (a) Transmission coefficient S21 through the printed microstrip transmission line in the range from 100 kHz to 26.5 GHz and (b) surface resistance of silver films sintered at 200 °C and 250 °C, calculated from measurements of the S21 parameter.

Figure 4. (a) Photo of the double slot aerosol jet printed antenna on flexible polyimide substrate and (b) typical SEM image of the surface.

Samples of microantennas with sintering temperatures of 200 °C and 250 °C were prepared. A typical photo of an antenna printed on a flexible polyimide substrate is shown in figure 4a. Figure 4b shows SEM image of the antenna surface sintered at 250 °C. The measured return loss, S11-parameter, of antennas sintered at 200 °C and 250 °C is shown in Figure 5. Also figure 5 shows the results of an
FDTD simulation of an antenna made of a Perfect Electric Conductor (PEC) and having resistances of 0.3 Ohm sq⁻¹ and 0.5 Ohm sq⁻¹, which corresponds to the frequency of 10.5 GHz.

![Figure 5](image.png)

**Figure 5.** Measured return loss of the aerosol jet printed antenna and FDTD simulation.

4. Conclusion
Aerosol jet printing method can be used to form antennas on flexible polymer substrates. The agreement between microwave losses of printed antennas and the FDTD simulation is observed, taking into account the parasitic interaction of the antenna with the measuring cable. The measured bandwidth of the antennas is more than 1 GHz at a level of −10 dB, which corresponds to 10% of the center frequency. Thus, the possibility of forming antennas on flexible polymer substrates with high functional characteristics by aerosol jet printing method has been demonstrated.

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