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Design of Kapton based passive circuits at microwave frequencies

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Abstract—This paper presents a technology based on thin flexible polyimide substrate (Kapton) to develop passive circuits at microwave frequencies. In the first step, we characterize the Kapton polyimide (relative permittivity and loss tangent) by using a ring resonator method. Then a 60 GHz patch antenna is designed, fabricated, and measured to validate our technology. Finally, a design of cross slot dipole antenna with a large bandwidth at 60 GHz is proposed.

Keywords—Flexible substrate technology; Kapton RF characterization; Passive circuits.

I. INTRODUCTION

There is an increasing demand of high efficiency antennas and passives for applications where high frequency operation, lightweight, and conforming to a curved surface are required. Flexible electronics has spanned impressively over the past years, and flexible substrate became a strong competitor versus his rigid substrate counterparts because they are typically more rugged, lighter, portable and less expensive to manufacture [1].

TABLE I. Comparative properties of state-of-art flexible substrates [2]

Material	PET	PEN	Kapton	LCP	Paper
Mechanical properties	Good	Good	Excellent	Good	-
Heat resistance	Low	Very good	Excellent	Good	-
Chemical resistance	Good	Good	Good	Excellent	-
Electrical properties	Good	Good	Good	Good	Good

The choice of flexible substrate for the applications at microwave frequencies is a challenge, because the substrate must exhibits good electrical (e.g. low losses) mechanical and chemical properties. Moreover, the substrate should keep these electrical properties over a wide range of frequencies and under external conditions such as temperature and pressure etc.

Finally, substrates used in RF devices should be able to withstand the rigors (e.g. humidity, gasing) of its operating environment and of the fabrication processes used in its packaging [3].

Several flexible substrates used for printed circuit packaging are listed in TABLE I. One can see the characterizations for polyethylene terephthalate (PET) [4], polyethylene naphthalate (PEN) [5], Kapton [6], liquid crystal polymers (LCP) [3] and paper-based substrate [7]. LCP has a nearly constant relative permittivity of 3.1 and low loss ($\tan \delta = 0.002 \sim 0.005$) up to millimeter wave frequency range, near-hermetic nature (water absorption $< 0.04\%$) makes it suitable for high frequency designs. The paper is a good candidate for its low cost, but it has limitations issues related to high frequency, absorption, and humidity. Finally, we selected Kapton as substrate for the development of our passive circuits due to its good RF and thermal properties, very good flexibility over a wide temperature range (-73°C to $+400^\circ\text{C}$) and its resistance to many chemical solvents.

The most widespread technologies used in microfabrication are photolithography, screen printing, and inkjet printing. (Fig.1). Inkjet printing is a direct write technology which presents a low cost advantage because the design pattern is transferred directly to the substrate and does not require masks. However, using this technology for millimeter wave applications could be a challenging task because of the highly required accuracy. Since both screen printing and inkjet printing can only offer highest resolution around $20\ \mu\text{m}$ [8], the traditional photolithography remains most suitable method for microfabrication at this frequency range.

This paper is organized as follows. The second chapter presents a description of the fabrication process we have developed, followed in the third chapter by a study of Kapton dielectric properties using a ring resonator method. Then, the design of a grounded coplanar waveguide feeding patch

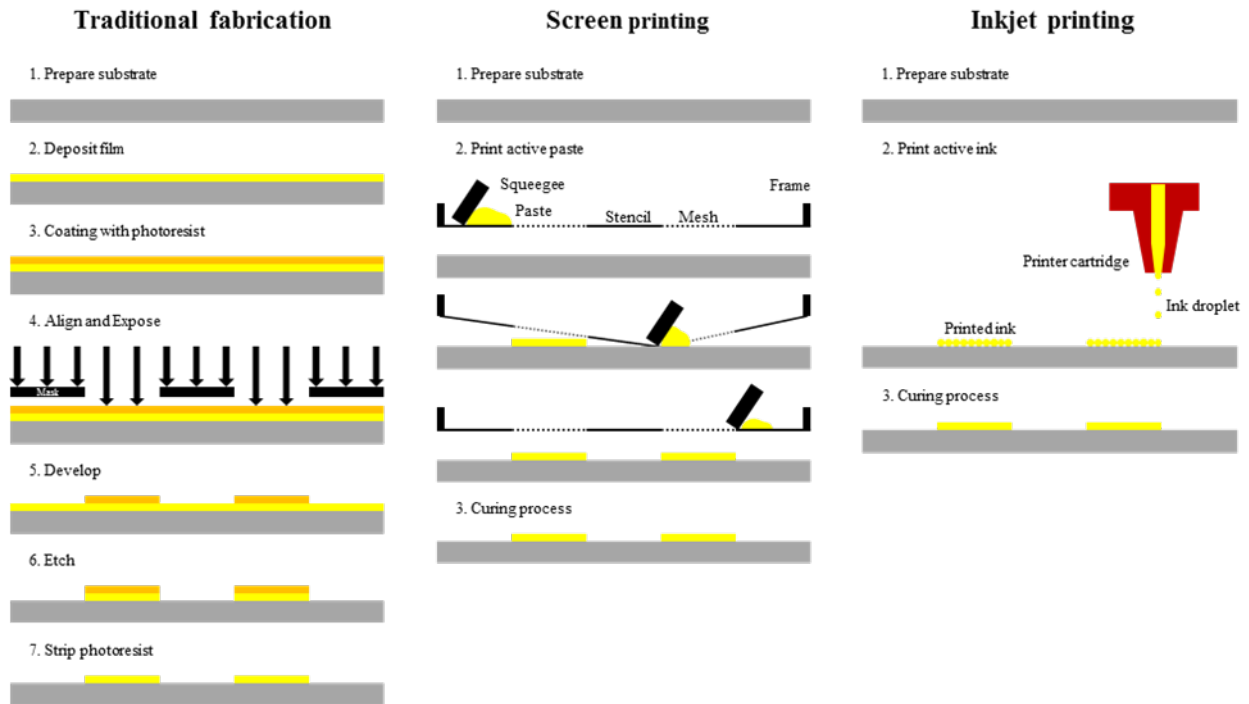


Fig. 1. Comparison of the processing steps involved in subtractive microfabrication, screen printing and inkjet printing [9].

antenna on a 127- μm -thick Kapton in the 60 GHz band is described. Its main features in impedance and radiation are discussed. Finally, a design of cross slot dipole antenna with a large bandwidth at 60 GHz is proposed.

II. TECHNOLOGICAL PROCESS FOR FLEXIBLE SUBSTRATE INTEGRATION

To manufacture our circuits onto a flexible substrate, we have chosen the traditional photolithography, the mainly difficulty during the fabrication process lies on the flexible film handling and its use in micro-technology equipment, in order to overcome this difficulty, a 4-inch silicon wafer is used as a host carrier. One of the critical obstacles consists of finding a way to adhere the polyimide film on the Si support. This adhesion has to be compatible with the various technological stages (vacuum, solvent and temperature) and allows after manufacture a peeling without any physical or chemical constraint.

A well matured fabrication process is used to spin coating a polymer for the adhesion of the polyimide on the holding wafer. Then the Kapton polyimide is patterned on the substrates by lamination. A resin spin coating is then realized followed by a photolithography process for the metallization layer [10].

III. RF CHARACTERIZATION OF KAPTON

To start the design of any high-frequency structure by using numerical simulation, the knowledge of dielectric properties of the substrate becomes necessary. A commercially 127- μm Kapton (type 500HN) was chosen for our substrate, the value

of thickness is in fact imposed by an effective patch antenna design in V-band. The antenna is composed by a rectangular patch on the top side of the substrate and a ground plane on the back side. Thus a minimum thickness must be respected to avoid undesired capacitive effect and to ensure a high-efficient radiation mechanism. A study of influence of thickness versus maximum antenna gain (simulation HFSS [11]) is given in Fig. 2. One can see that thicker the substrate, a better antenna gain can be obtained regardless the type of metallization.

The dielectric properties of Kapton: the relative permittivity ϵ_r and the loss tangent $\tan \delta$ were extracted from S-parameters measurement of ring resonator, which is composed by a ring with mean radius 4.265 mm, the width of microstrips on the Kapton surface is 306 μm to make sure that the characteristic impedance of the microstrips is 50 Ω . There are two 80 μm gaps at the end of the ring to couple the resonator to the measurement system, which provides us sufficiently coupling to measure the resonators without loading too much the test equipment.

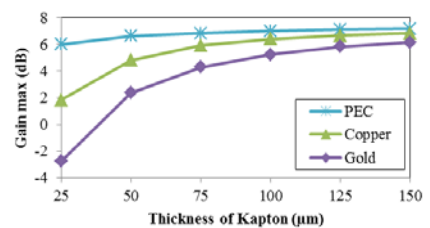


Fig. 2. Maximum antenna gain versus substrate thickness.

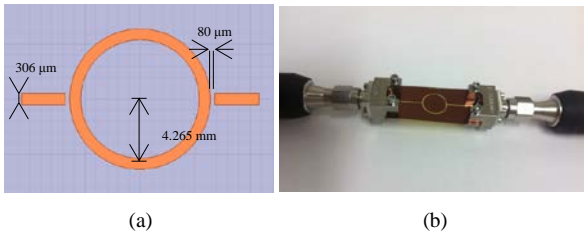


Fig. 3. (a) Ring resonator design and (b) manufactured ring resonator with two K "End-Launch" connectors.

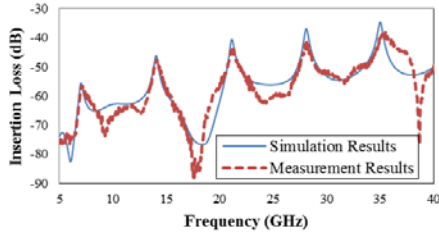


Fig. 4. Simulated and Measured Insertion Loss of the ring resonator.

IV. DESIGN AND MEASUREMENT OF KAPTON BASED PASSIVE CIRCUITS

A. Patch antenna

A 60 GHz grounded coplanar waveguide (GCPW) feeding rectangular patch antenna (see Fig. 5(a)) was designed, fabricated, and measured on a flexible 127- μm -thick polyimide substrate (Kapton). The GCPW-to-microstrip transition was optimized with the help of HFSS electromagnetic (EM) software in order to minimize the impedance mismatch. The antenna was then characterized in terms of return loss, gain, and radiation pattern.

The simulated and the measured return losses of the patch antenna versus frequency are presented in Fig. 6. The agreement between experiments and simulations is quite good: a relative frequency shift of only 1.4% is observed between the simulated (HFSS) and measured results. It could be due to uncertainty in the substrate permittivity value and under/over etching of the conductive patterns. The measured bandwidth, defined by return loss less than -10 dB, is from 62.4 GHz to 64.4 GHz.

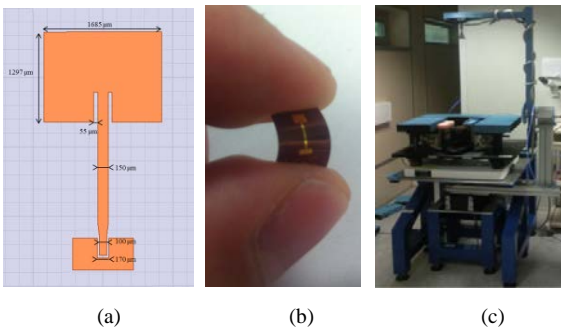


Fig. 5. (a) 60GHz GCPW feeding rectangular patch antenna, (b) Demonstration of the flexibility of patch antenna on Kapton., (c) Antenna radiation measurement setup.

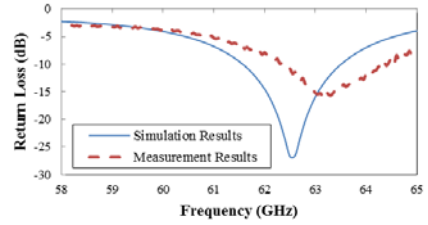


Fig. 6. Simulated and Measured Return Loss of the patch antenna.

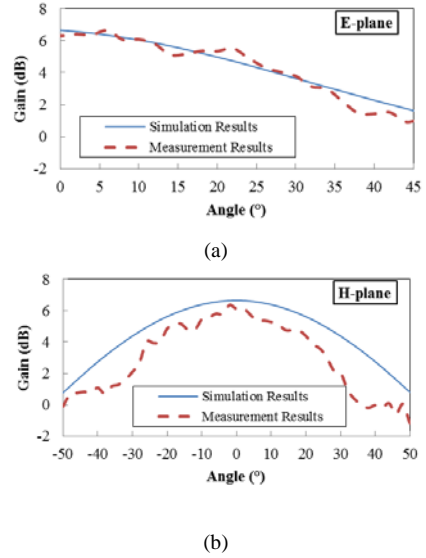


Fig. 7. (a) E-plan and (b) H-plan radiation patterns of the patch antenna at 63.2 GHz.

The far-field radiation pattern and gain were measured with a probe based antenna measurement setup at LAAS-CNRS (Fig. 5(c)). The antenna is fed through a 150- μm Ground-Signal-Ground (GSG) probe, and this probe is directly connected to a 65 GHz VNA (Anritsu 37397D) with a flexible V-cable. Dielectric foam (Rohacell) was used on the bottom to prevent reflections from the metallic part of the setup. The antenna under test (AUT) was illuminated by a field generated by a calibrated horn antenna in the 60GHz band with a gain around 25 dBi.

Under these conditions, a maximum gain of 6.31 dBi was found in the perpendicular direction of the patch antenna around 63 GHz. The simulated and measured radiation patterns in the E- and H-plan are given in Fig. 7. The E-plan radiation pattern has a restricted range due to architecture of the measurement setup. Pronounced ripples are observed in the E-plane due to reflection and diffraction effects on the metallic micro-positioner and the probe. The 3-dB beam width for the E-plan is 64° and 52° for the H-plan.

The results demonstrate the quality of fabrication on flexible polyimide substrate and the accuracy of measurement setup for microwave antennas implementation.

B. Cross slot dipole antenna

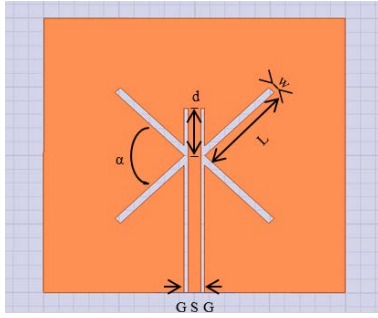


Fig. 8 . 60 GHz CPW fed cross slot dipole antenna.

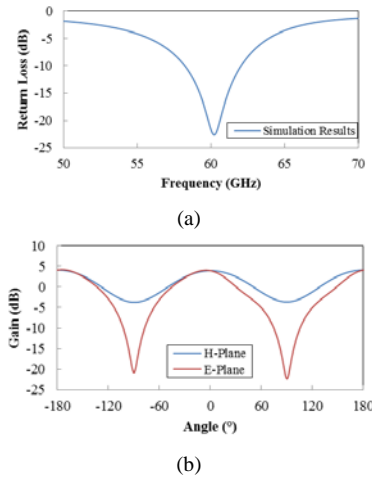


Fig. 9. (a) Simulated Return Loss of the cross slot dipole antenna and (b) radiation patterns in E-Plan and H-Plan at 60.2 GHz.

The geometry of the proposed cross slot dipole antenna fed by a CPW is depicted in Fig. 8, the antenna is designed on a 127- μm thick Kapton with a dielectric constant 3.2 and a loss tangent 0.002. CPW feed dimensions of $S = 170 \mu\text{m}$ and $G = 12 \mu\text{m}$ were selected corresponding to the 50Ω GSG probe. The slot length L is fixed to 2.5 mm (quarter wavelength for 60 GHz) for the simulation, the slot width w , the stub length d and the angle between slots α were set to $40 \mu\text{m}$, 0.69 mm and 45° as default respectively.

Fig. 9(a) shows the simulated return loss. The center frequency is 60.2 GHz, and the -10 dB bandwidth is from 58.2 GHz to 62.05 GHz. The antenna radiation patterns were also presented in Fig. 9(b), a peak antenna gain of 4.02 dB is obtained at 60.2 GHz.

TABLE II. Study of angle α effect on radiation

α ($^\circ$)	f_c (GHz)	Return Loss (dB)	Maximum Gain	HPBW ($^\circ$)
40	59.7	-21.09	4.14	82
45	60.2	-22.76	4.02	86
50	61.15	-27.48	4.08	90

A parametric study for the angle between slots is shown in TABLE II. It is seen that when the angle α increase, the peak antenna gain decrease along with a larger half power beamwidth (HPBW) on H-plan due to the more important coupling effect when two slots approach to each other.

V. CONCLUSION

In this work, we demonstrate the feasibility of manufacturing microwave passive circuits at high frequency with very good RF performances through a traditional photolithography on a commercially available polyimide substrate. A quite good agreement between the measurements and simulations has been obtained. Future measurement for the cross slot dipole antenna will be carry on. This work is one step further towards a heterogeneous integration on flexible substrate of different components for wireless sensor nodes.

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