Temperature Dependency (25 °C–400 °C) of a Planar Folded Slot Antenna on Alumina Substrate

Maximilian C. Scardelletti, *Senior Member, IEEE*, Jennifer L. Jordan, *Member, IEEE*, and George E. Ponchak, *Fellow, IEEE*

***Abstract*—The dependency of planar folded slot antenna characteristics fabricated on alumina substrates over the temperature range of 25 to 400 °C are presented. The 3.575 GHz antenna is fed by a 20 mm long, 50 Ω CPW line ($S = 130$ and $W = 60$ μm), and there is no ground plane on the back side of the substrate. An on-wafer TRL calibration was used to deembed the CPW feed line for return loss measurements and to measure the increase in the effective dielectric constant and attenuation of the CPW lines as a function of temperature. The measured antenna characteristics show that the resonant frequency varies by less than 1%, the minimum return loss increases from 11 to 16 dB, the quality factor increases from 25.5 to 44.75, and the gain decreases by 1 dBi as temperature is increased from 25 °C to 400 °C. Finally, the effect of the measurement test setup on the measured radiation patterns is discussed.**

***Index Terms*—Absolute gain, alumina, folded slot antenna, high temperature, return loss.**

I. Introduction

THE ability to transmit and receive data in harsh environments, especially from *in-situ* sensors, is increasingly gaining interest for commercial and military applications. Wireless sensors that can be used in harsh environments to transmit critical data back to a diagnostic counterpart can alleviate hard wire connections and other electronics otherwise required to complete the data path. Wireless sensors for industrial applications such as mining and oil drilling are required to operate at 300 °C, and aircraft engine sensors that would be placed outside of the combustion area and behind the manifold are being developed that must operate at 400 °C. In addition, NASA is planning science missions to Venus, which has a surface temperature of 450 °C. The antenna is an integral part of these systems and a full understanding of how the impedance match, bandwidth, radiation pattern, and gain vary as a function of temperature is required to optimize data transmission and reliability.

Characterizing antennas within a harsh environment is challenging and little information has been presented on this topic. In [1], the substrate's electrical parameters were measured from 25 to 80 °C, and these were used to calculate the variation in the return loss of a patch antenna over the temperature range of 25 to 80 °C. Note that metal resistivity variation with temperature was not accounted for in the calculations. Hauser measured the resonant frequency of a patch antenna on an alumina substrate and showed that it decreased approximately 30 MHz, from 2450 to 2420 MHz, over a temperature range from 25 °C to 200 °C. The authors of this letter reported preliminary measurements of the return loss of a CPW fed folded slot antenna (FSA) fabricated on alumina substrates at 25 and 300 °C [3]. However none of these papers present the antenna radiation patterns or gain as a function of temperature.

This paper presents the measured characteristics of a CPW fed, folded slot antenna fabricated on alumina as a function of temperature for the first time. Return loss, bandwidth, radiation pattern, and gain are presented at temperatures of 25 °C, 50 °C, 100 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, and 400 °C. In Section II, the antenna design, fabrication and measurement method are presented. Section III presents the simulation technique using HFSS [4], and Section IV presents the results.

II. Antenna Design Fabrication and Measurement

A. Antenna Design and Fabrication

The FSA, shown in Fig. 1, was designed to operate at 5 GHz and utilizes an internal self-matching technique, the antenna slot widths are designed to match the antenna to the feed line without external matching networks [5]. The antenna slot dimensions are: $a = d = 0.1, b = 0.85, c = 16.5, e = 0.9, f = 10$ and $g = 13.7$ mm. A 20 mm long 50 Ω coplanar waveguide (CPW) transmission line was used to feed the antenna. The antenna was fabricated on 99.6% polycrystalline Al_2O_3 (alumina) substrate with a dielectric constant of 9.9 and a thickness of 500 μm. The CPW metal layer consists of chrome (Cr) and gold (Au) with thicknesses of 200 Å and 1.3 μm, respectively.

B. Measurement Procedure

To measure the return loss of the antenna as a function of temperature, a special probe station with modified ground-signal-ground (GSG) probes was used [6]. A TRL calibration was performed at every temperature using on-wafer standards and Multical calibration software [7]. The changes in attenuation and

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The authors are with the National Aeronautics and Space Administration Glenn Research Center at Lewis Field, Cleveland, OH 44135 USA (e-mail: Maximilian.C.Scardelletti@nasa.gov; Jennifer.L.Jordan@nasa; George.E.Ponchak@nasa.gov).

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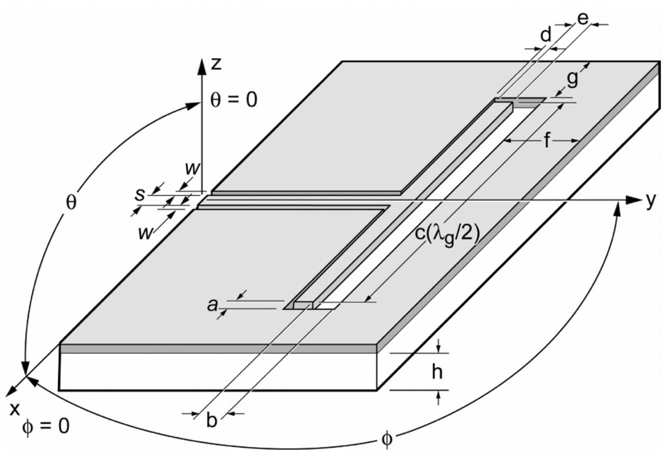

Fig. 1. Drawing of folded slot antenna detailing dimensions of antenna slots.

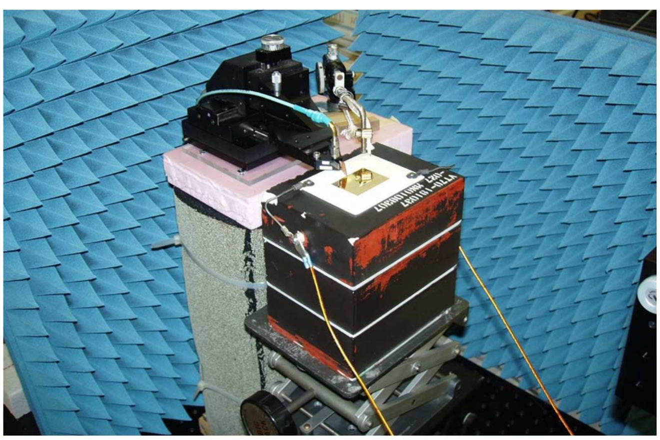

Fig. 2. Modified test set up to characterize radiation patterns.

effective dielectric constant (ε_{eff}) of the CPW feed lines were recorded.

Characterizing the radiation patterns of the antenna required a modification to a novel on-wafer measurement technique presented by Simons [8] and is shown in Fig. 2. The ceramic heater, shuttle tile chuck and GSG probes of [6] replaced the RF probe station in [8] to accommodate the measurements at the elevated temperatures. A longer Plexiglas arm was added to the rotational stage to ensure the radiation patterns were measured in the farfield range. As shown in Fig. 2, the ceramic heater sets on 6 inches of shuttle tile, which is supported by a metal scissor jack. Two wires from a DC power supply are connected to the ceramic heater and a metal probe arm is required to position the thermocouple on top of the substrate. These metal structures affect the radiation pattern as described in the next section. Due to physical constraints of the measurement technique used to characterize the radiation patterns, only a 180° and 90° sweep could be performed on the H- and E-planes, respectively.

To calibrate the antenna measurement system, the GSG probe was placed on the metal ground section of the antenna to simulate a short circuit and the reflected power level was recorded at every temperature. One half of the difference between each temperature setting reflected power level and the room temperature

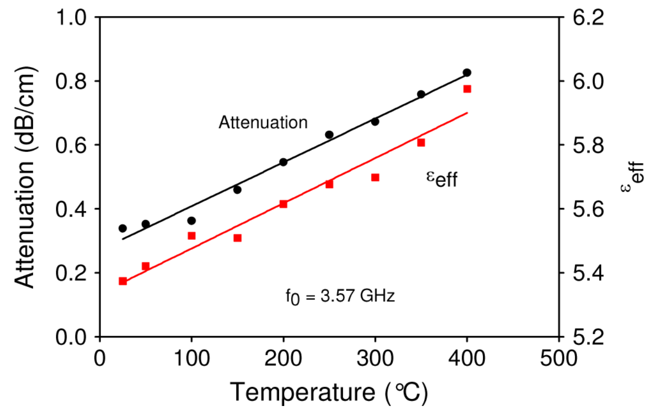

Fig. 3. Attenuation and effective dielectric constant at $f_0 = 3.57$ GHz.

reflected power level was added back to the measured radiation pattern to account for the variation in loss from the GSG probes and RF cables over the temperature range. This calibration normalizes all of the data to the room temperature measurements.

III. Simulated

Simulations were performed using Ansoft's HFSS 3-D electromagnetic simulator. To account for the rise in temperature, the conductivity of the gold metal layer was decreased according to (1)

$$S_1 = \frac{S_2}{[1 + n(T_1 - T_2)]} \quad (\mathrm{S/m}) \tag{1}$$

where S_1 is the conductivity value at T_1, S_2 is the conductivity value at T_2, and n is the temperature coefficient. From CRC handbook, $\mathrm{S}_2 = 41 \times 10^6$ S/m at $\mathrm{T}_2 = 25°\mathrm{C}$ and $\mathrm{n} = 0.0037/°\mathrm{C}$. The relative permittivity was also increased at every temperature setting to account for the increase in effective dielectric constant measured in Section IV.

IV. Results

Multical was used to determine the attenuation and ε_{eff} of the CPW feed line and are shown in Fig. 3. The attenuation of the CPW lines gradually increases from 0.37 to 0.84 dB/cm as the temperature increase from 25 to 400 C. ε_{eff} increases from 5.4 to 6, approximately 10%, over the same temperature range. This is agreeable with [9], [10] when taking into account the metal cladding thickness.

The measured return loss at every temperature setting is shown in Fig. 4. The ceramic heater has a dielectric constant of approximately 4.4, which causes the resonant frequency of the antenna to shift from the design frequency of 5 to 3.575 GHz. The effect of the ceramic heater was verified through simulation from HFSS. The resonant frequency varies by less than 1% over the temperature range, which differs from [2]. This is due to the self-matching technique used to match the radiating slot of the FSA to the 50 Ω CPW feed line. As ε_{eff} increases, the resonant frequency decreases but the impedance matching section offsets the shift in resonant frequency and the net affect is a constant impedance match. This phenomenon was verified

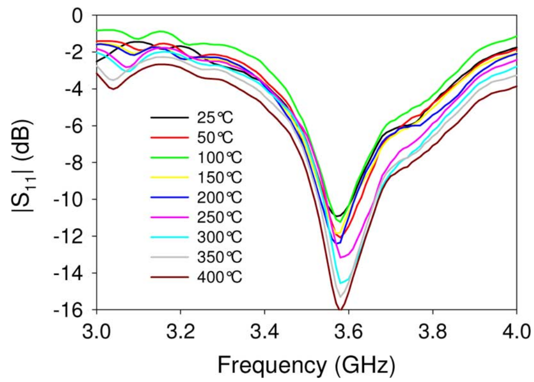

Fig. 4. Return loss of the folded slot antenna as a function of temperature.

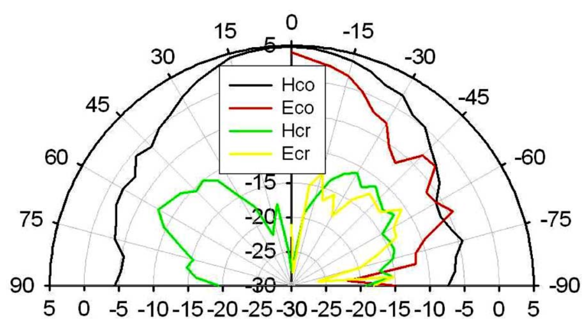

Fig. 5. H and E-co-and -cross radiation patterns measured on Styrofoam.

in HFSS over the temperature range. Preliminary measurements in [3] reported a shift in resonant frequency, but further measurements confirmed that this was due to small variations in the location of the antenna during tests. The return loss minimum decreases by roughly 5 dB as temperature increases from 25 °C to 400 °C. In addition, the antenna quality factor, Q, increases from 25.5 to 44.5 as the temperature increases. Thus, while the frequency bandwidth of the antenna decreases with increasing temperature, the frequency of optimum match remains constant.

Knowing the return loss was effected by the ceramic heater, it was decided to first characterize the radiation pattern of the FSA on a Styrofoam support, which would simulate the freespace environment that the antenna would see in use. Fig. 5, shows that the H co-plane is oval in shape while the E co-plane is bidirectional, the typical pattern of a non-grounded FSA [5]. The gain and the 3 dB BW are approximately 4.8 dBi and 60°, respectively. The cross polarization levels are more than 10 dB down from the co-polarization patterns.

The H and E-co and -cross patterns as a function of temperature are displayed in Fig. 6(a) to (d). There are obvious effects of the metal scissor jack 6 inches under the antenna as evidenced by distortions in the H-co pattern. The gain has also decreased by 1.3 dB compared to the antenna measured on Styrofoam. To verify that the scissor jack is responsible for the pattern change, the antenna was simulated in HFSS on top of a ceramic heater, 6 inches of shuttle tile and a metal plate to represent the scissor jack. The simulations verify that the metal jack causes the ripples in the pattern. The E-co shows very much the same response. As a function of temperature, it is seen that the shape of the radiation patterns or the level of the cross-pol does not vary.

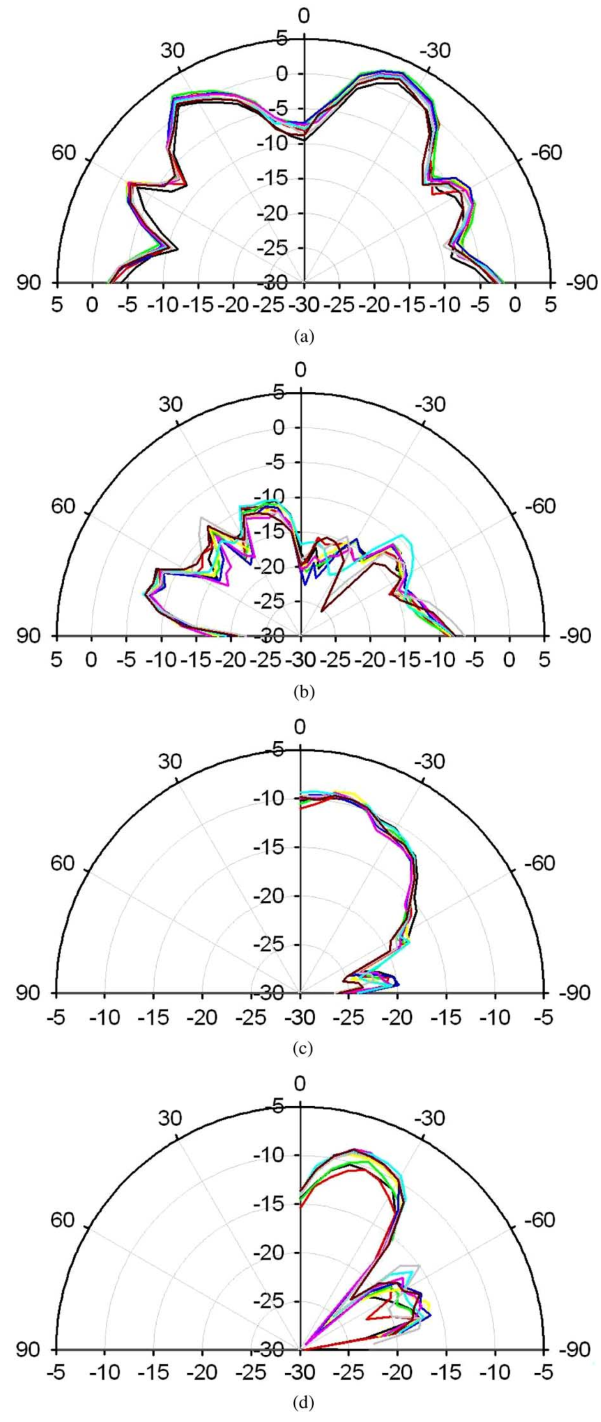

Fig. 6. (a) H-co, (b) H-cross, (c) E-co, and (d) E-cross radiation patterns illustrating very little change in shape and gain over the temperature range from 25 °C to 400 °C.

The gain was measured using the substitution method and recorded at 3.57 GHz. Fig. 7 shows the gain of the antenna with the CPW feed line as a function of temperature, where it is seen that the gain decreases from 1.5 dBi to 0 dBi as temperature increases. In addition, Fig. 7 shows the gain of the antenna after subtracting the loss of the CPW feed line. When the increased

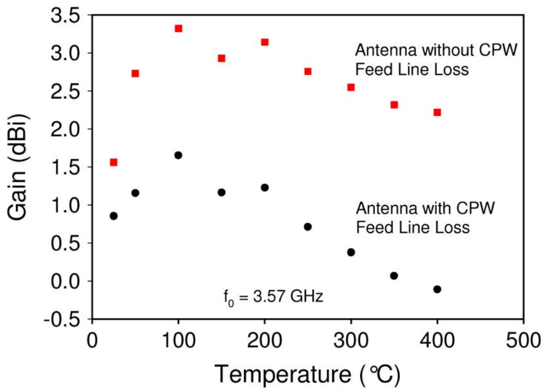

Fig. 7. Measured antenna gain with and without the CPW feed line loss at 3.57 GHz.

feed line loss is subtracted, it is seen that the antenna gain still decreases, but only by 1 dB.

V. Conclusion

Temperature dependency of microfabricated planar folded slot antennas on alumina substrates from 25 °C to 400 °C has been presented. The resonant frequency of the antenna does not vary with temperature even though the effective permittivity of the CPW feed lines increased by 10% as temperature increased. However, the Q of the antenna did increase with temperature. The radiation patterns did not vary with temperature, but the antenna gain decreased by 1 dBi. Based on these results, the folded slot antenna is acceptable for high temperature wireless sensor applications.

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