The Temperture Dependence of Substrate Parameters and Their Effect on Microstrip Antenna Performance

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***Abstract*—In the common approach to the design of microstrip antennas, the designers rely on data provided in the manufacturers' specifications, even though such specifications are confined to standard environmental conditions. In practice, the electrical parameters of the substrates may deviate from the manufacturers' data, thus making the antenna designer adopt a deficient design strategy. In the study reported in this paper, microstrip substrates were exposed to large temperature variations and their temperature dependent properties were measured in a specialized laboratory for dielectric materials. The results include plots of the dielectric constant and dissipation factor for wide temperature ranges equivalent to those in airborne applications. On the basis of this experimental data, the substrates were divided into four categories according to their dielectric constant value and its temperature dependence. Using both manufacturers' data and the measured values, a series of microstrip dual-feed aperture-coupled patch antennas were designed for the four categories of substrates and the sensitivity of their electrical performance due to temperature variations was fully investigated.**

***Index Terms*—Dielectric measurements, printed antennas, thermal factors.**

I. Introduction

RECENT years have witnessed an increased use of microstrip patch antennas in radio communications and radar. In some of these applications, a patch antenna is required to operate in an environment, that is close to what is defined as room or standard conditions. However, antennas often have to work in harsh environments characterized by large temperature variations. Air and spaceborne applications fit these characteristics, as well as large-scale integrated microwave antenna modules (in the latter, the antennas are thermally affected by the adjacent electronic active stages). The result is that the electrical properties of microstrip antennas suffer from unwanted variations.

In the course of our study, we found that two major problems had not been clearly addressed in the antenna literature [1]. The temperature dependence of the electrical parameters of the substrates and the discrepancies between actual values and those quoted in the manufacturers' specifications. These aspects are evidenced by the common practices regarding the design and development of patch antennas, which neglect these problems. In a typical approach to the design of a microstrip patch antenna, the values of dielectric constant and dissipation factor are assumed as quoted in the data sheets. There, the dielectric constant value (ε_r) generally falls within a certain tolerance range, while for the dissipation factor ($\tan\delta$), the maximum value is postulated. The manufacturers usually emphasize the frequency dependence of the material, neglecting the temperature drift. Few data sheets provide the thermal coefficient of ε_r, which applies to the temperature range from 0 °C (32 °F) to +100 °C (212 °F).

It is often the approximate nature of the theoretical models or the CAD tools used in the design process that are blamed for the discrepancies between the predicted and actual performances of the antennas. This judgment can be deficient when the actual electrical and physical substrate parameters deviate from those of the data sheet or when they are both temperature and frequency dependent.

In the present study, teflon-based laminates, ceramic-based laminates, and quartz-fiber composite substrates are investigated. The electrical parameters of these materials are difficult to measure accurately at the running manufacturing line. This may be one of the reasons why the manufacturers' data is often incomplete or incorrect. We obtained accurate temperature characteristics of different substrates by using a precisely controlled laboratory setup. Having determined the actual electrical parameters of several substrates, investigations are performed into the variations of the electrical performance of microstrip antennas due to the incorrectly assumed electrical and physical parameters of the substrates.

II. Effect of Temperature on Dielectric Constant and Dissipation Factor

Of the various materials used in microstrip technology, teflon, ceramic, and polystyrene laminates, dielectric foams and honeycomb composites have already found wide acceptance. The present study looks at the behavior of the ε_r and $\tan\delta$ values in some microwave materials (at four test frequencies: 800 kHz, 1 MHz, 1 GHz, and 10 GHz), when they are exposed to considerable temperature variations. In our testing procedure they ranged from −60 °C (−76 °F) to +80 °C (176 °F). Such temperature changes are experienced

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in airborne applications, although in spaceborne applications they can be approximately twice as high.

In the present study, substrate measurements were performed at the Laboratory of Dielectrics and Structure of Organic Compounds at the Chemistry Faculty of the Wroclaw University, Poland. The laboratory has well-established facilities providing high-quality measurements for solid and liquid materials at temperatures ranging at least from −120 °C (−184 °F) to +180 °C (356 °F) at arbitrary humidity and in the presence of various chemical agents.

The samples were disc shaped and had diameters of 8 and 6 mm for low frequencies and high frequencies, respectively. They were prepared with extreme care as exertion of any physical force could adversely affect the electrical parameters of the sample. It was due to the large frequency span that two measuring methods and three test setups had to be used. Thus, at 800 kHz and 1 MHz use was made of a Hewlett Packard HP4284A precision LCR meter. Relative permittivity and loss tangent were calculated assuming a parallel plate capacitor model for the sample. At frequencies higher than 1 MHz, the resonant method was applied, using a HP4191A RF Impedance Analyzer for frequencies of up to 1 GHz and a HP 8720C Vector Network Analyzer, HP 817A-Slot Line and custom-made microwave test cavity for frequencies ranging between 1–10 GHz. In every instance the cavity with the sample under test was installed inside a hermetic cavity with precise temperature control. The measuring setup was calibrated using standard polypropylene or polystyrene samples of known parameters. Regardless of temperature, the accuracy of the measurements was quite good, with errors smaller than 1.5 and 3% for dielectric constant and dissipation factor, respectively. It should be noted that the measuring accuracy is affected by the precision of the microwave equipment and by the quality of dielectric material sample preparation. In the latter, the maintenance of a constant sample thickness is of paramount importance. Furthermore, materials displaying very low losses (less than 0.001) could be measured with worse accuracy of $\tan\delta$ parameter. More details concerning the measurement accuracy of this parameter can be found in [2].

Using the testing facility of the laboratory, the dielectric constants and the dissipation factors of laminates and substrate materials offered by major manufacturers (Rogers, 3M-Arlon, Taconic, CuFlon, GIL) were measured. Due to the anisotropic properties of the laminates, the measurement plane had to be clearly defined. In the present case, the measurements were performed only in the z plane that was oriented along the laminate thickness.

The investigated substrates were divided into four categories, A, B, C, and D, according to the composition of the material and the temperature dependence of the dielectric constant. Categories A and B included teflon-glass microwave laminates. Substrates of Category A were characterized by dielectric constants whose values decreased with temperature where the drop had approximately constant gradients, which varied slightly when a phase transition of glass occurred. Note that the phase transition phenomenon involves changes in molecular thermal mobility, which is associated with transformations of the amorphous phase of materials, from a glassy

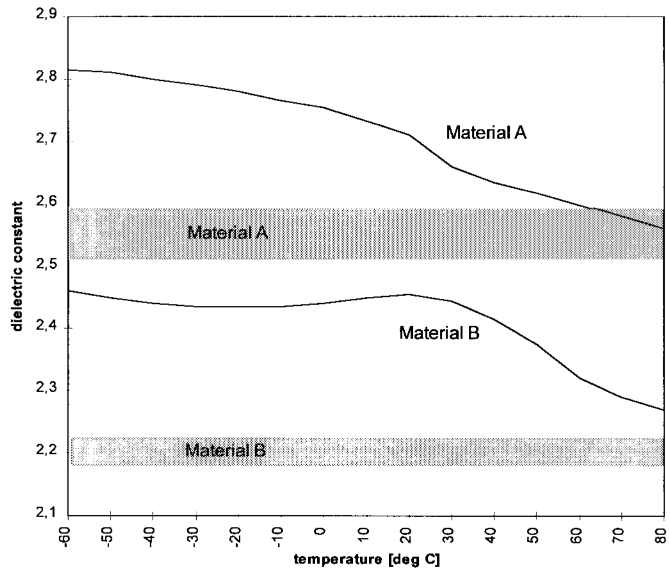

Fig. 1. Measured dielectric constant (ε_r) for two categories (A and B) of glass-reinforced teflon laminates.

(low-mobility) to a rubbery (high-mobility) state [3]. Phase transition in glass occurs at 20–30 °C (68–86 °F) and is accompanied by a variation in the dielectric constant and dissipation factor and by an increase in the thermal expansion coefficient.

Category B laminates were characterized by a dielectric constant with a gradient value differing markedly in at least two temperature subranges of the dielectric constant plot. Regardless of this effect, the laminates experienced phase transition. It is worthwhile to mention that the Category B laminates had dielectric constants, which were almost independent of temperature in the lower temperature subrange and showed a remarkable temperature dependence in the upper subrange.

The laminates were made of woven or dispersed glass fibers and teflon fillers (at precisely controlled proportions of glass and filler). Although there is a wide spectrum of glass types, only some of them, namely those having low losses at microwave frequencies (e.g., pyrex) can be used for the manufacture of microwave laminates. All of the laminates tested belonged either to Category A or B. Thus, representative examples of Category A were Ultralam 2000 and CuClad 250 LX laminates, while good representative examples of the Category B were RT/duroid 5880 and TLX-8 laminates. Unfortunately, it is impossible to classify a given laminate as A or B on the basis of data sheets, because the latter do not provide sufficient information about the chemical composition of the glass or material structure.

Categories C and D materials included ceramic and quartz-fiber composites, respectively. We do not mention the names of the materials or manufacturers when providing quantitative data.

The measured temperature characteristics of the dielectric constant for two laminates representing Categories A and B, respectively, are plotted in Fig. 1. As shown in this figure, the measured values for material A ranged from 2.82 at −60 °C to 2.56 at +80 °C (a 9.7% change). There was a

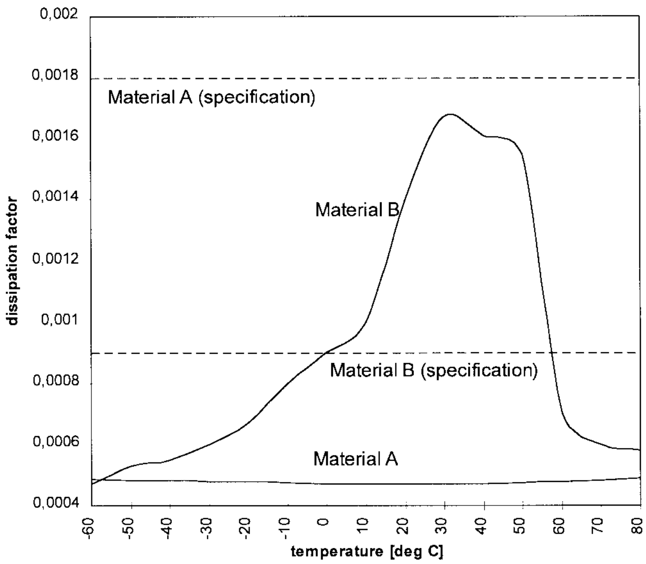

Fig. 2. Measured dissipation factor ($\tan \delta$) for two categories (A and B) of glass-reinforced teflon laminates.

noticeable phenomenon of glass phase transition, as observed at 23 °C (73 °F). For the material representing Category B, the measured dielectric constant ranged from 2.46 at −60 °C to 2.45 at +20 °C and 2.27 at +80 °C (an 8% change). The changes in the dielectric constant as a function of frequency (within the considered temperature ranges) for laminates A and B were less noticeable. The relative change in the dielectric constant as a function of frequency was less than 0.15% for material A and less than 0.5% for material B. The measured temperature characteristics of the dissipation factor for both laminates are presented in Fig. 2. The measured value for laminate A approached 0.0005 and was almost frequency independent. This value was much lower than the one quoted in the manufacturer's specification. The highest measured value of the dissipation factor for laminate B was close to 0.0017 at temperatures between +30 °C (86 °F) and +50 °C (122 °F), and complied with the data sheets only for a limited temperature range. Having measured the values of the dielectric constant for laminates A and B, it was interesting to compare them with the values specified by the manufacturers. The comparison revealed a considerable discrepancy between the measured values and those quoted by the manufacturers. Furthermore, it disclosed the occurrence of phase transition at about 20–30 °C (68–86 °F). This has not been mentioned in the manufacturers' specifications.

In the course of testing, we noticed that exerting a high pressure onto the laminates' surfaces irreversibly modified the electrical properties of the substrate, increasing, for example, the value of the dielectric constant. However, generally pressing the laminates under high temperature cannot be avoided during the photo-etching process, because it is necessary to clad a light-sensitive film onto the laminate surface.

Category C materials were laminates with uniformly dispersed ceramic filler in a teflon matrix. Typical examples of this category are RT/duroid 6010 and AR1000. Fig. 3 shows the measured dielectric constant and dissipation factor values for one of the Category C laminates. The measured

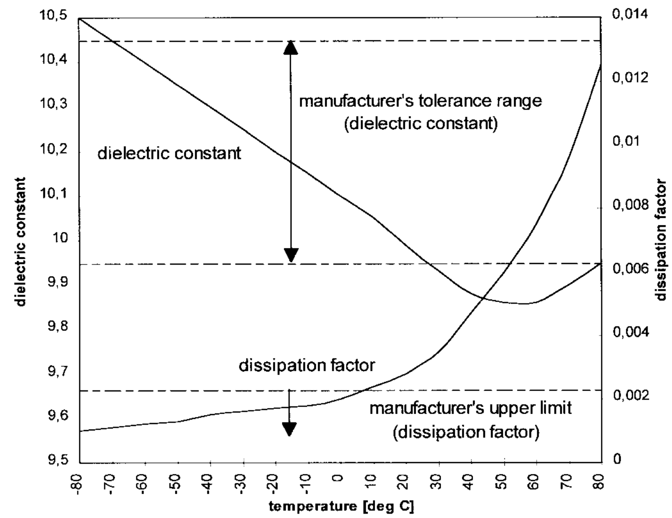

Fig. 3. Measured dielectric constant value for a cooled and warmed ceramic filler laminate C.

dielectric constant value changed by 6.9%. There was negligible variation in the dielectric constant with frequency in the temperature range of −60 °C to +25 °C (77 °F) and a slight variation with frequency in the higher temperature range, reaching a maximum of 0.8% at +80 °C. The values of dissipation factor measured at a room temperature amounted to 0.003—being 1.3 times the maximum value given by the manufacturers' specification. Only for temperatures below +10 °C did the dissipation factor comply with the value recommended in the specification. Temperatures above +10 °C had a considerable effect on the measured values and led to a significant divergence from the specifications at high temperatures. The highest measured dissipation factor value was 0.012 at +80 °C, which was 5.2 times the maximum allowable value given by manufacturers' specifications. The measured values did not show any temperature-related hysterisis as they were independent of cooling and warming sequences.

III. PERFORMANCE OF MICROSTRIP ANTENNAS OVER LARGE TEMPERATURE RANGES

Having measured the electrical parameters of the substrates, it is possible to perform a comprehensive analysis of various microstrip antenna elements exposed to large temperature variations. In the present study, our considerations were focused on a dual-feed aperture-coupled microstrip antenna, which was designed for operation in the downlink of a personal satellite communication system. The downlink frequency band adopted for the purpose of the study ranged between 2483.5 and 2500 MHz (16.5-MHz bandwidth with center frequency $f_0 = 2491.75$ MHz).

The generic view of the investigated antenna is shown in Fig. 4. The antenna structure consists of three dielectric layers, one ground plane, and printed circuits. On the top surface there is a square patch. Two orthogonal rectangular coupling slots are located in the ground plane. On the bottom surface there is a microstrip feeding circuit comprising two separately excited microstrip lines. Since this antenna has two orthogonal feeds, it can generate dual-polarized or circularly polarized

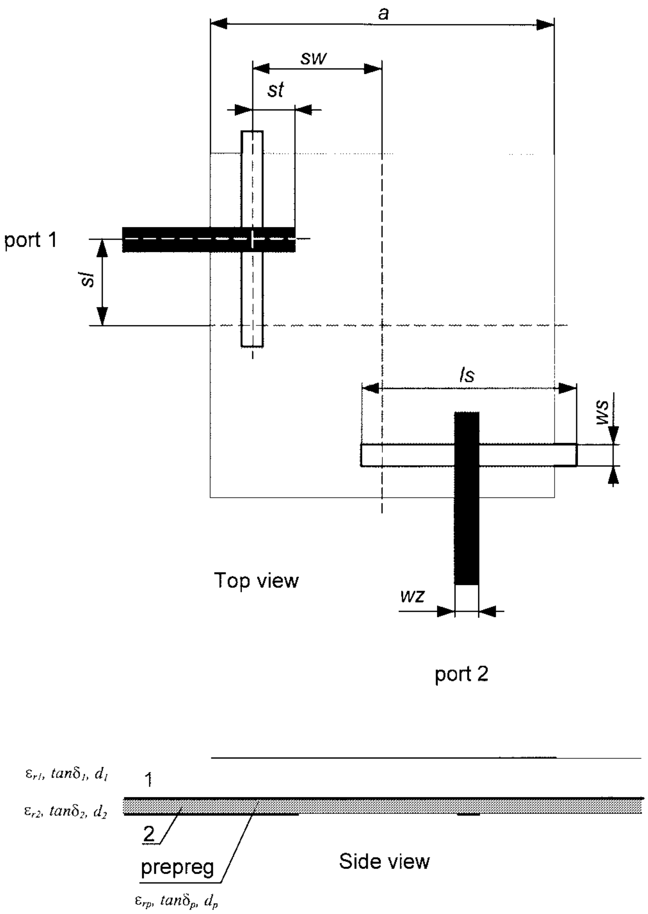

Fig. 4. Configuration of a dual-feed patch antenna with through-slot coupled microstrip lines. Metal cladding: 0.5-oz (17.5 μm) thick copper. Ports 1 and 2 are located between branch coupler and coupling apertures.

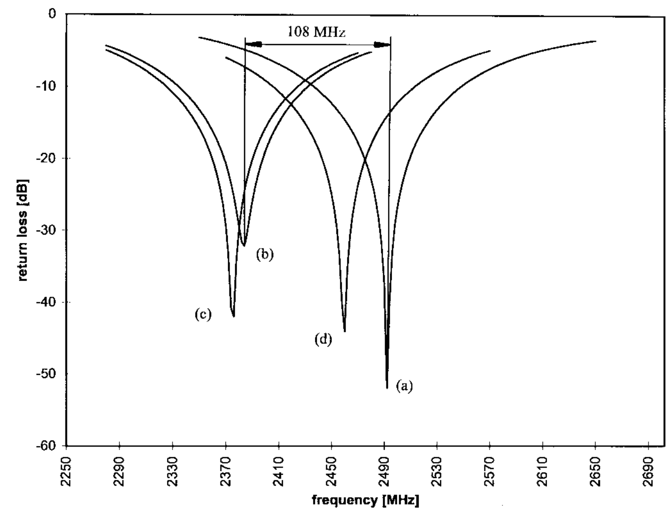

Fig. 5. Calculated return loss at ports 1 and 2 (S_{11} and S_{22}) of a LBB patch antenna of Fig. 4, with different sets of electrical parameters (ε_r and $\tan\delta$) of the substrates: (a) provided by the manufacturer; (b) measured at +20 °C; (c) measured at −60 °C; and (d) measured at +80 °C. Both substrates were made of material B. $a = 34.66$ mm, $ls = 23.2$ mm, $ws = 2.0$ mm, $sw = 12.4$ mm, $sl = 7.0$ mm, $wz = 2.42$ mm, $st = 6.0$ mm, $\varepsilon_{r1} = \varepsilon_{r2}$, $\tan\delta_1 = \tan\delta_2$, $\varepsilon_{r1} = \varepsilon_{r2} = 2.20$, $\tan\delta_1 = \tan\delta_2 = 0.0009$, $d_1 = 3.18$ mm (125 mils), $d_2 = 0.76$ mm (30 mils), $\varepsilon_p = 2.32$, $\tan\delta_p = 0.0013$, $d_p = 40\,\mu$m.

electromagnetic radiation. To obtain circular polarization, it is necessary to use an external polarizer in the form of a 3-dB directional coupler connected to the two lines. In all the investigated cases, the patch substrate was chosen to be 3.18 mm thick (125 mils). The microstrip line and the feeding circuit substrate were 0.76 mm (30 mils) or 0.51 mm (20 mils) thick. Between the patch substrate and the ground plane there was a thin bonding film. Note that in aerospace composite engineering the term “bonding layer” is also known as *prepreg*. All circuits were printed on 17 μm (0.5 oz) copper foils.

In the investigations presented here, attention was focused on the return loss characteristic (S_{11} and S_{22}) as a function of frequency and, particularly, on the temperature drift of the center frequency, (defined as the maximum return loss frequency). Although isolation between the two ports is a key parameter in the design of dual- or circularly polarized antenna elements, it was not the subject of the present investigations. The reason is that for the dual or circularly polarized antenna, there exists a tradeoff between the return loss and isolation when broad-band operation is required. In such a case, the return loss has to be decreased in order to achieve high-feed isolation and, consequently, an increased polarization bandwidth. However, having decreased the return loss value, the position of the center frequency is less clearly determined and, therefore, does not provide a clear measure of the frequency drift. Nevertheless, for the cases investigated here for which the return loss at the center frequency was maximized, the isolation values ranged between 9.5–16.7 dB and was only slightly sensitive to temperature.

For accuracy of analysis, the software package Ensemble (Ansoft, Boulder Technologies) was used. This software involves a full-wave method and is suitable for analyzing printed antennas that are manufactured in stratified planar dielectrics. During calculations, the frequency step was set to 2 MHz, except in selected cases where it was made to be 1 MHz. The calculated results were slightly affected by the grid size. For example, for a coarse grid, the calculated center frequency was 2508 MHz while for a fine grid it was 2492 MHz, as required. In the present analysis, an even temperature distribution across the entire antenna structure was assumed. In practice, the temperature distribution inside the antenna structure can be nonuniform. In such cases, a more complex analysis may be required. However, they are not considered here.

A. Antennas with Laminates A, B, and C

We considered several antenna designs. For clarity, they were denoted by three letters. The notation reads as follows: the first latter (L or P) indicates the source from which the electrical parameters of the substrate were taken (L = manufacturers’ data, P = our measurements). The second letter stands for the patch substrate category (A, B, and D). The third letter denotes the category of the feeding line substrate (A, B, and C). The return loss characteristics calculated for an LBB antenna, with manufacturer’s specified parameters (l) for the teflon-glass laminate substrate (b) of the feedline and patch layers, is shown in Fig. 5. Thus, the patch and microstrip line substrates belonged to substrate category B (with temperature characteristics shown in Figs. 1 and 2). The lowest $S_{11}(S_{22})$

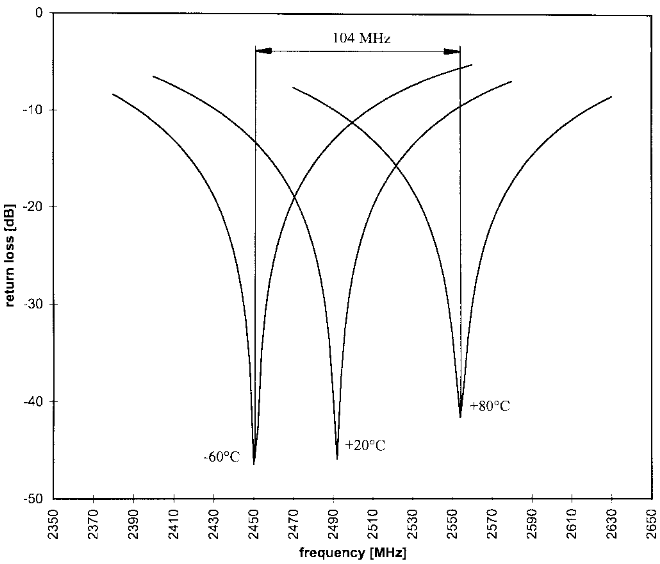

Fig. 6. Calculated temperature dependence of return loss (S_{11} and S_{22}) of PAA patch antenna designed with the use of the measured material electrical parameters. Both substrates were made of material A (Figs. 1 and 2). $a = 31.1$ mm, $ls = 22.6$ mm, $ws = 2.0$ mm, $sw = 11.5$ mm, $sl = 6.5$ mm, $wz = 2.04$ mm, $st = 5.3$ mm, $\varepsilon_{r1} = \varepsilon_{r2}$ and $\tan\delta_1 = \tan\delta_2$ are the measured values, $d_1 = 3.18$ mm (125 mils), $d_2 = 0.76$ mm (30 mils), and $\varepsilon_p = 2.32$, $\tan\delta_p = 0.0013$, $d_p = 40\mu$m.

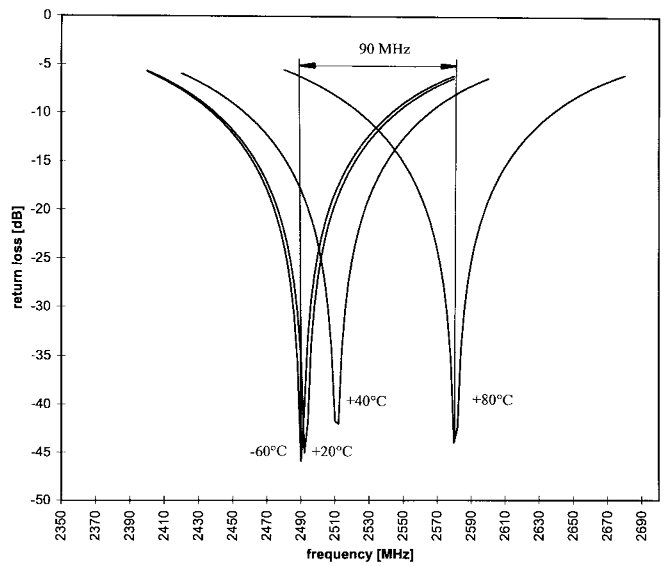

Fig. 7. Calculated temperature dependence of return loss (S_{11} and S_{22}) of PBB patch antenna, designed with the use of the measured material electrical parameters. Both substrates were made of material B (Figs. 1 and 2). $a = 33.2$ mm, $ls = 22.0$ mm, $ws = 2.0$ mm, $sw = 12.0$ mm, $sl = 6.5$ mm, $wz = 2.18$ mm, $st = 6.0$ mm, $\varepsilon_{r1} = \varepsilon_{r2}$ and $\tan\delta_1 = \tan\delta_2$ are the measured values, $d_1 = 3.18$ mm (125 mils), $d_2 = 0.76$ mm (30 mils), $\varepsilon_p = 2.32$, $\tan\delta_p = 0.0013$, $d_p = 40\mu$m.

value was −52 dB at $f_0 = 2492$ MHz and the 10 dB return loss bandwidth was 108 MHz. It is interesting to recalculate the return loss characteristics of the LBB antenna by making use of measured electrical parameters of the laminate. Plots (b)–(d) of Fig. 5 present the results of such calculations for three temperatures, respectively. The plots of the antenna return loss for the measured values show a considerable shift downwards along the frequency axis. The center frequency at +20 °C amounted to 2384 MHz (being by 108 MHz lower than the design value). The 10 dB return-loss bandwidth of the antenna was 97 MHz (which is concomitant with the decrease of the minimum return loss value). The drift of the center frequency was 84 MHz when temperature varied between −60 °C and +80 °C. This frequency drift was several times the required operational bandwidth. The results imply that the designed antenna would not satisfactorily fulfill the requested technical specifications. Needless to say, such an antenna could hardly be regarded as a good design. We also examined how the presence of prepreg affected the return loss characteristics. The influence of prepreg was found to be very small as the center frequency was shifted by only about 2 MHz.

If the center frequency of an actual antenna falls below the design value, this may be an indication that the actual dielectric constant value of the substrate has been greater than the one assumed in the course of design. In our tests all laminates had a greater measured dielectric constant values than the nominal ones.

Figs. 6 and 7 show the calculated return loss characteristics for the PAA and PBB antenna, with own-measured parameters (P) of category A or B teflon-glass laminate substrates used in the feedline and patch layers, respectively. In both designs, use was made of actual electrical parameters, as obtained from measurements at +20 °C. The center frequency drift caused by temperature variations was −42 MHz (at −60 °C) and +62 MHz (at +80 °C) for the PAA antenna, and −2 MHz (at −60 °C) and +88 MHz (at +80 °C) for the PBB antenna. The antenna bandwidth approached 7% and increased slightly with temperature. For the PBB antenna, the frequency drift was only 22 MHz in the temperature range from −60 °C to about +40 °C. A major section of the drift occurred at temperatures above +40 °C. That can be attributed to the temperature dependence of the dielectric constant value of laminate B.

Since the use of the same substrates for the patch and for the feeding network may not necessarily provide an optimal patch design, we also studied antennas involving a combination of teflon-based (A or B) and the ceramic-based (C) laminates. Fig. 8 presents the plot of S_{11} values calculated for the PAC antenna (material C, 0.51 mm thick). The center frequency offset due to temperature was −42 MHz at −60 °C and +50 MHz at +80 °C. The impedance bandwidth approached 110 MHz and increased slightly with temperature. The PAC antenna presented the first design that complied with the return loss (10 dB) requirement over the specified frequency band and over the entire investigated temperature range.

B. Antennas with Material D

On the basis of the results obtained in the subsection A we can see that the use of glass reinforced teflon substrates may be unacceptable in applications were the antennas are exposed to large temperature variations. Hence, it is worthwhile to look for materials with electrical properties less susceptible to temperature. Advanced aerospace composite materials are promising candidates for consideration. There are two principal categories of such composites—one based on honeycomb fillers and the other one based on fibers (glass or quartz). The

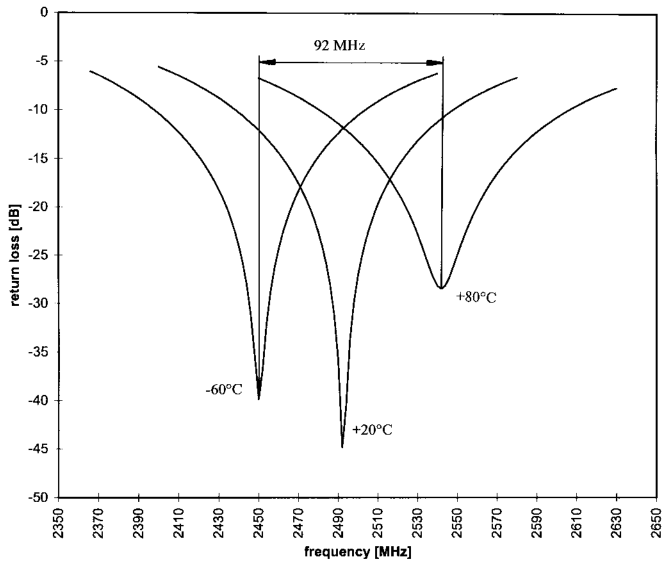

Fig. 8. Calculated temperature dependence of return loss (S_{11} and S_{22}) of PAC patch antenna, designed with the use of the measured material electrical parameters. Patch substrate: 125-mils-thick material A (Figs. 1 and 2); line substrate: 20-mils-thick material C (Fig. 3). $a = 31.2$ mm, $ls = 21.3$ mm, $ws = 1.6$ mm, $sw = 11.6$ mm, $sl = 7.0$ mm, $wz = 0.488$ mm, $st = 2.8$ mm, ε_{r1}, ε_{r2}, $\tan\delta_1$, and $\tan\delta_2$ are the measured values, $d_1 = 3.18$ mm (125 mils), $d_2 = 0.76$ mm (30 mils), $\varepsilon_p = 2.32$, $\tan\delta_p = 0.0013$, $d_p = 40\mu$m.

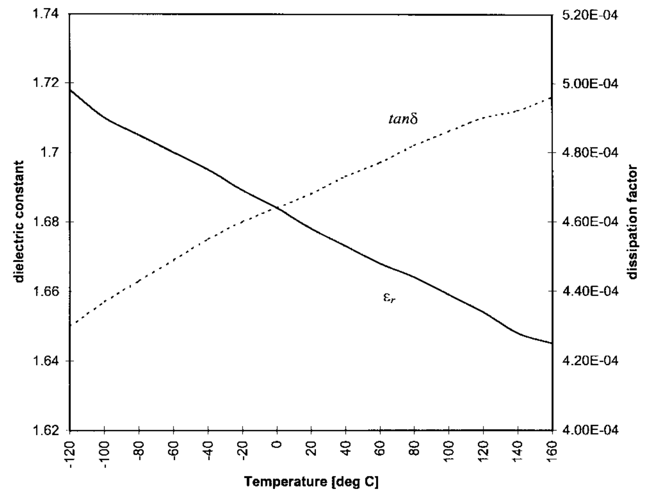

Fig. 9. Measured electrical parameters in a wide temperature range of quartz-fiber-based composite (material D).

major advantages of these materials can be detailed as follows: low weight or ultralow weight, very wide temperature range of operation, good electrical parameters, weak temperature dependence of electrical parameters, and small thermal expansion coefficient. In our study, we considered composites made of quartz fibers (category D substrates). The deficiency of the material was fragility, moisture absorption, and difficulty of cladding of printed circuits.

One of the recently recommended Category D materials for use in microstrip antennas is a quartz-based composite, which consists of short quartz fibers bonded together. The development of this material was originally stimulated by the needs of thermal insulation engineering. The measured dielectric constant and dissipation factor for this material are plotted in Fig. 9 for test temperature ranging from −120 °C (−184 °F) to +160 °C (320 °F), which complied with the conditions of certain spaceborne applications. Compared to the materials of Category A, B, or C, the dielectric constant value of the Category D material varied only slightly: from 1.718 at −120 °C to 1.645 at +160 °C (4.3%). The dissipation factor turned out to be ultralow, varying from 0.00 043 at −120 °C to 0.0005 at +160 °C. Manufacturer's data were unavailable, because this material is recommended for other applications. It has to be added that frequency had little effect on the measured values and there were no phase transitions.

Using the Category D material, a new dual-fed microstrip antenna (PDB) was designed (the thickness of the Category B laminate being 30 mils). Fig. 10 shows the calculated return loss (S_{11} and S_{22}) versus frequency with temperature as a parameter. The maximum return loss, 56 dB, was achieved at 20 °C and was higher than 24 dB in the entire operating frequency bandwidth. The center frequency drifted with temperature from 2480 MHz (−60 °C) to 2506 MHz (+80 °C). The PDB antenna return loss was never worse than 15.6 dB over the entire operating temperature (−60 °C to +80 °C) and frequency band.

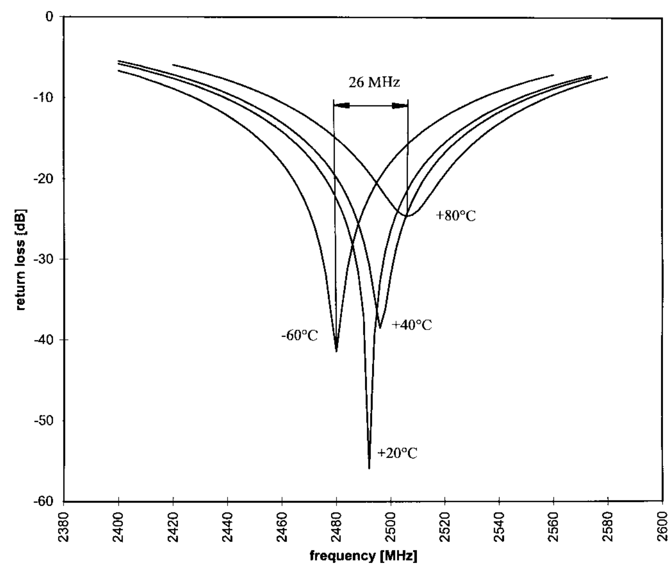

Fig. 10. Temperature drift of calculated return loss (S_{11} and S_{22}) of PDB patch antenna, designed with the use of the measured material electrical parameters. Patch substrate: 125-mils-thick composite material D (Fig. 9); line substrates: 30-mils-thick material B (Figs. 1 and 2). $a = 39.14$ mm, $ls = 24.6$ mm, $ws = 2.0$ mm, $sw = 14.5$ mm, $sl = 9.0$ mm, $wz = 2.18$ mm, $st = 5.8$ mm, ε_{r1}, ε_{r2}, $\tan\delta_1$, and $\tan\delta_2$ are the measured values, $d_1 = 3.18$ mm (125 mils), $d_2 = 0.76$ mm (30 mils), $\varepsilon_p = 2.32$, $\tan\delta_p = 0.0013$, $d_p = 40\mu$m.

Having achieved such promising results for the PDB antenna, we examined a PDC antenna in which the 30-mils-thick teflon-based laminate had been replaced by a 20-mils-thick ceramic laminate of Category C. The calculated return loss characteristic is shown in Fig. 11. The center frequency varied by 22 MHz (from −16 MHz at −60 °C to +6 MHz at +80 °C). The return loss was even lower than that for the PDB antenna. It must be noted that for the substrate combinations B + D and C + D, a remarkably small frequency drift was achieved (1 and 0.9%).

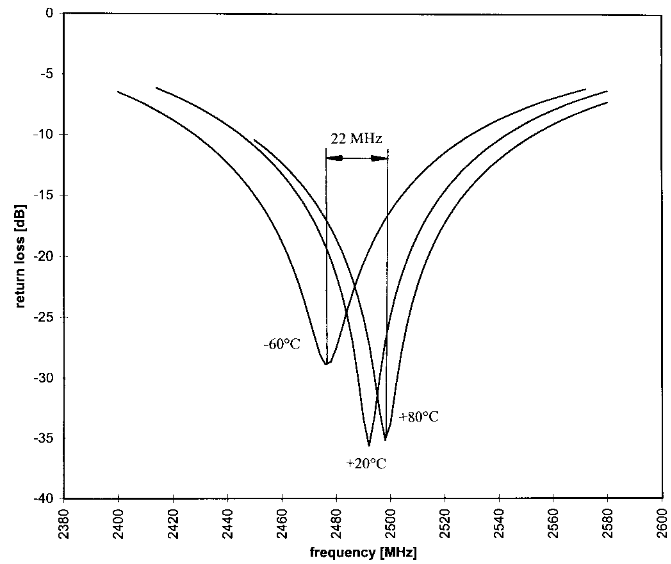

Fig. 11. Temperature drift of the calculated return loss (S_{11} and S_{22}) of PDC antenna, designed with the use of the measured material electrical parameters. Patch substrate: 125-mils-thick composite material D (Fig. 9); line substrate: 20-mils-thick material C (Fig. 3). $a = 39.8$ mm, $ls = 22.0$ mm, $ws = 1.6$ mm, $sw = 14.7$ mm, $sl = 10.0$ mm, $wz = 0.488$ mm, $st = 3.2$ mm, ε_{r1}, ε_{r2}, $\tan\delta_1$ and $\tan\delta_2$ are the measured values, $d_1 = 3.18$ mm (125 mils), $d_2 = 0.51$ mm (20 mils), $\varepsilon_p = 2.32$, $\tan\delta_p = 0.0013$, $d_p = 40\mu$m.

C. Thermal Expansion Effect

So far we described the temperature dependence of the electrical parameters of the substrates and their effect on the performance of the patch antenna. However, in a practical situation, there are other substrate-related factors that affect the performance of antennas. One of them is the thermal expansion coefficient. Thermal variations account for a slight expansion or shrinkage of the antenna dimensions. Yet the expansion effect and the temperature dependence of the substrate electrical properties may compensate each other.

The thermal expansion coefficient in the x and y directions (parallel to the laminate surface) generally ranges from 14 to 48 ppm/ °C. Thus, in practice, the impact of the thermal expansion coefficient along the x or y axis for a moderately sized substrate is of little importance. Hence, in the present case, for the investigated temperature variations between -60 °C and $+80$ °C, the expansion in the x and y directions can be neglected. The values of the thermal expansion coefficient in the z direction for glass-reinforced teflon laminates generally range from 170 to 280 ppm/ °C. For an expansion coefficient of 280 ppm/ °C, the thermal expansion of a 0.76-mm-thick laminate (at $+20$ °C) results in a 3.9% thickness change [from 0.7430 mm (29.25 mils) at -60 °C to 0.7728 mm (30.43 mils) at $+80$ °C]. For a 3.18-mm-thick board, thickness also changes by 3.9%, but the corresponding values are 3.109 mm (122.39 mils) and 3.233 mm (127.30 mils) for -60 °C and $+80$ °C, respectively. The thermal expansion coefficient of a quartz-fiber composite is more than one hundred times smaller than that for many other types of foams used for microstrip antennas. The composite D (Fig. 9) has an ultra low coefficient of thermal expansion, ranging from 4×10^{-7} to 7×10^{-7}. For a 3.18-mm-thick board, this expansion coefficient leads to 0.01% thickness changes.

TABLE I
CALCULATED CENTER FREQUENCY AND THE MAXIMUM RETURN LOSS WITH AND WITHOUT INCLUSION OF THERMAL EXPANSION EFFECT

Antenna	center frequency [MHz] return loss [dB]			
	without thermal expansion		with thermal expansion	
	-60°C	+80°C	-60°C	+80°C
PAA	2450	2554	2449	2555
	46	41	38	60
PBB	2490	2580	2489	2582
	46	44	32	35
PDB	2480	2506	2478	2507
	41	24	53	24
PDC	2476	2498	2477	2498
	29	35	27	37

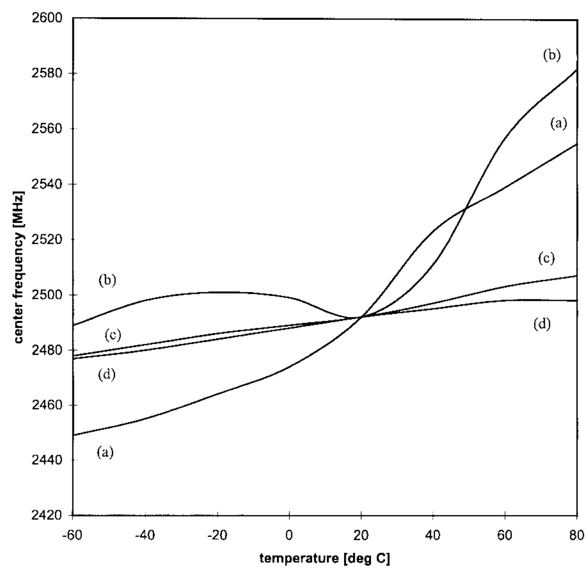

Fig. 12. Center frequency defined in terms of the minimum value of S_{11} (S_{22}), versus temperature for antennas. (a) PAA. (b) PBB. (c) PDB. (d) PDC.

It is worth evaluating how thermal expansion contributes to the overall antenna parameters. From the data of Table I (comparing the center frequency and maximum return loss with and without inclusion of the thermal expansion effect) it is apparent the change in the physical dimensions of the antenna has little importance. The frequency step used in the calculations was 1 MHz. Fig. 12 describes the calculated center frequency drift when the thermal expansion effect was included in the analysis. As shown by these plots, frequency drift due to temperature was 106 MHz for the PAA, 93 MHz for the PBB, and 21 MHz for the PDC antenna.

IV. Conclusions

This paper has presented a thorough study into the performance of microstrip patch antennas that are exposed to large temperature variations. Four material categories have been selected for the purpose of this study: teflon-glass (Categories A and B), ceramic-teflon laminates (Category C), and quartz-fiber composites (Category D). The obtained results allow the following general comments. For microwave laminates, the measured dielectric constant and dissipation factor often differ from the values recommended in the data sheets. What is more, in all of the investigated cases the measured dielectric constant value was greater than the one specified in the data sheets. In general, the manufacturers' specifications are valid only for a limited temperature range. Hence, the values provided by relevant data sheets are inadequate when the substrate is exposed to large temperature variations. This deficiency is due to the temperature dependence of the dielectric constant of the microwave laminates studied. In consequence, the electrical characteristics of microstrip antennas that involve layered dielectrics are considerably influenced by temperature. Of these characteristics, the drift of the resonant frequency and the return loss characteristics may raise serious concern. A careful selection of the substrate dielectrics that are least sensitive to temperature variations is a prerequisite to accomplish a satisfactory antenna design. It has been shown that replacing the feedline layers with ceramic substrates can minimize temperature-related variations in the antenna performance. Further improvement can be achieved using quartz-fiber composites. Investigations into the thermal expansion of the substrate have shown that this phenomenon is of minor importance.

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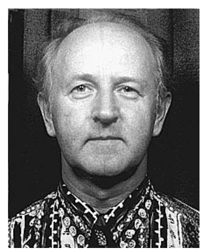

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