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A COMPARISON OF SOME LOW COST LAMINATES FOR ANTENNAS OPERATING IN THE 2.45 GHZ ISM BAND

Max J. Ammann*

Abstract
An evaluation of some low-cost laminates suitable for microstrip patch antennas is presented. Criteria for the selection of substrates for antenna fabrication are given careful consideration. A coaxial-probe fed linearly-polarized rectangular microstrip patch operating at a frequency of 2.45 GHz was fabricated on four different low-cost laminates. The substrates used were polyester, epoxy glass (FR-4), a ceramic filled PTFE composite and a woven glass-reinforced hydrocarbon and ceramic thermoset material. Material properties are discussed and the antenna performances are evaluated and compared to one fabricated on a thick glass-loaded microfiber PTFE substrate. An evaluation of some inexpensive microstrip antenna CAD packages, which employ closed-form expressions based on transmission-line and cavity models, is also given. These models ignore the diffraction effects of a finite ground-plane.

Low cost microstrip antenna CAD

There are many CAD packages available which are very useful for microstrip antenna design. The following are some of the low-cost packages available today. *PCAAD 3.0* (Personal Computer Aided Antenna Design) is a computer package, written by Pozar [1], which contains many routines for the design and analysis of antennas. It includes a fundamental treatment of the patch antenna based on a cavity model and deals with linearly-polarized circular and rectangular geometries.

PatchD is one of a series of stand-alone executable files, written by Sainati [2], that analyse and solve microstrip problems. It is based on a series of closed form expressions which were generated by curve-fitting to numerical solutions obtained by solving the full field equations. *Patch9* is another program by Sainati in the same series, which is based on the transmission-line model. An accuracy of about 2 % is claimed and it is limited in application to thin substrates. The series cover both linearly-polarized and circularly-polarized geometries and also two-layer patches and superstrates.

Ouray Microstrip Antenna Designer 2.03 [3] is a recent addition to the low-cost microstrip antenna CAD arena. It is mainly based on the transmission line model but employs the cavity model for bandwidth and efficiency calculations. The directivity and gain are calculated using equations derived from curve-fitting moment method results. It deals with rectangular and circular geometries for a variety of modes and includes superstrates. It also computes radiation patterns, power handling capability and frequency variation due to manufacturing tolerances. The nearly-square single-feed CP patch is also covered.

One drawback for these packages is that they do not produce artworks, but the calculated dimensions can be input to *EasyPC, Puff* or currently available drawing or graphics packages, taking care to note the resolution of the package and printing device. Another drawback is that the edge-diffraction effects of a finite groundplane are ignored. This effect can significantly reduce the accuracy of the models used. However, many of the more expensive software packages which employ full-wave analyses also assume an infinite groundplane and suffer from the same drawback; these, however, can normally handle multilayer arrays and the effects of surface waves, possible mutual-coupling and spurious radiation. They can also produce

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artworks for complex geometries. For wireless applications in this frequency band, surface wave effects are minimal, and mutual-coupling effects may be ignored, unless arrays are used with small spacing between elements or patches are fabricated on thick substrates of high relative permittivity [4].

One model reported by Huang [5] is based on slot theory and includes the effects of a finite groundplane by employing uniform theory of diffraction (UTD). The rectangular patch is modelled as 2 slots in a finite groundplane. It is very accurate in predicting radiation patterns for patches on groundplanes greater than one electrical wavelength. This is not commercially available as a package, but can be realised from reported work [5,6], using a FORTRAN code for the edge-diffraction coefficients and transition functions developed by the Ohio State University [7]. Many recent papers have reported new methods of dealing with these edge-diffraction effects, but have not yet been developed as dedicated microstrip software packages. *Ensemble 5.0* [8] is the first such package to include this effect, but does not fall into the low-cost category.

Low-cost laminates

Costs are incurred both in the purchase of the laminate and in the subsequent processing. Some laminates, such as PTFE, require special processing techniques for fabrication and tooling, which are more expensive to process than FR-4 [9]. Some low-cost laminates may incurr excessive processing costs [10].

When selecting a substrate for *microstrip transmission lines*, a thin substrate with a high relative permittivity is preferred. This yields a physically smaller area with lower radiation efficiency. In contrast, when a substrate is chosen for a *microstrip antenna*, a thick substrate of low relative permittivity is a better choice. The low value of relative permittivity produces more loosely bound fields which enhance radiation efficiency. Wider lines have a higher radiation efficiency, so antennas normally employ wide (low-impedance) lines. The low value of relative permittivity also keeps the overall dimensions large, thus reducing requirements of dimensional tolerance. Other laminate parameters which must be considered are relative permittivity tolerance and anisotropy, thickness tolerance, loss tangent, copper weight, copper type, water absorption and substrate thermal properties. In general, the loss tangent should be below 0.005 for microwave applications. Copper weight should be greater than a few skin depths (1.3 μm at 2.45 GHz), but bearing in mind that the etching tolerance is of the order of the metallization thickness, and that undercutting may occur in narrow lines, if the metallization is too thick.. Surface roughness is not a problem for this application, so electrodeposited copper (EDC) is appropriate. 1 oz/(sq. ft) ED copper (35 μm) is a standard cladding and therefore is usually the most cost-effective, lighter copper weights are more expensive. Thermal properties may be a consideration; both the coefficient of thermal expansion and the thermal coefficient of dielectric constant may need to be considered where the antennas undergo temperature changes (e.g. aerospace applications) [11]. The 4003 laminate has one of the lowest thermal coefficients of ε_r, which is 40 ppm/°C. Water absorption is a measure of the percentage of moisture absorbed by the substrate when it is soaked in water for 24 hours at 23°C. This absorption will affect relative permittivity and loss tangent; it should be less than 0.1%. The following are some low-cost laminates currently available, the 5870 is listed for reference purposes.

Laminate	Dielectric substrate	ε_r	tan δ
5870*	PTFE / glass mix	2.33±0.02	0.0012 (10 GHz)
4003* [17]	glass / hydrocarbon /ceramic	3.38±0.05	0.0022 (10 GHz)
3003*	Ceramic filled PTFE composite	3.00±0.04	0.0013 (10 GHz)
NorCLAD [18]	Thermoplastic polyphenylene oxide	2.55	0.0011 (3.0 GHz)
GML 1000**	Polyester / resin	3.05±0.04	0.003 (2.5 GHz) 0.004 (10GHz)
FR-4	Epoxy / glass	4.2- 4.5±0.2	0.02 (1 MHz)

* Rogers Corporation, Chandler, AZ, USA.

**Glasteel Industrial Laminates, Colliersville, TN, USA, http:/gilam.com

Table 1

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For wireless antenna applications, a low-cost substrate with tight dielectric tolerance (< ±2%), low thickness tolerance (< ±5%) and low dissipation factor (tan $\delta < 0.005$) is required. The thermal coefficient of relative permittivity for a classic PTFE/glass mix is poor, with a definite step in the relative permittivity versus temperature curve at around 19°C [12]. The dielectric constant anisotropy due to fill materials may also be a consideration. Anisotropy may be defined as the condition in which the relative permittivity varies in value depending on the electric field orientation with respect to the axes of the substrate. The anisotropy for a woven PTFE/glass substrate with $\varepsilon_r = 2.45$ is 1.16. Microfiber PTFE with glass loading has better anisotropic properties; the 5870 ($\varepsilon_r = 2.33$) laminate has an anisotropy ratio of 1.04. Anisotropy increases with relative dielectric constant increase as more fill materials (glass) are added. Anisotropy ratios are generally as large as those quoted by manufacturers [13]. The anisotropy can be expected to increase the fringing capacitance, and hence affect the resonant length of the patch antenna because the fringing fields have significant components in the x-y plane.

Laminate	Dielectric substrate	ε_r tolerance (± %)	Thickness tolerance (± mm)	Thickness tolerance (± %)
5870	PTFE / glass mix	0.86	1.57±0.05	3.2
4003	glass / hydrocarbon /ceramic	1.48	1.52±0.10	6.6
3003	Ceramic / PTFE composite	1.3	1.52±0.08	5.0
NorCLAD	Thermoplastic polyphenylene oxide	n/a	1.52±0.08	5.0
GML 1000	Polyester / resin	1.3	1.52±0.08	5.0
FR-4	Epoxy / glass	5.0	1.52±0.15	9.8

Table 2

The maximum frequency variation (based on uncertainty analysis [14] and calculated using [3]) at 2.45 GHz due to the effects of etching tolerance, thickness and permittivity tolerances is 11 MHz for the 5870, 19 MHz for the GML1000 and is in excess of 60 MHz for FR-4. However, if the value of ε_r is measured for the FR-4, this frequency variation may be reduced.

Laminate	Dielectric substrate	Anisotropy	Water absorption (%)	Processing
5870	PTFE / glass mix	1.04	0.015	special
4003	glass / hydrocarbon /ceramic	≈ 1..1	0.060	as FR-4
3003	Ceramic / PTFE composite	≈ 1..1	< 0.100	special
NorCLAD	Thermoplastic polyphenylene oxide	n/a	0.060	as FR-4
GML 1000	Polyester / resin	1.017	0.020	as FR-4
FR-4	Epoxy / glass	n/a	0.100	as FR-4

Table 3

If cost were the most important factor in the choice of laminate, one would select FR-4. The relative permittivity of epoxy resin and the glass mix is 3.65 and 6.32 respectively. The FR-4 laminate has a dielectric constant calculable from the volume proportions of these two components. The percentage resin is normally between 40% and 55%. For a 50% mix, the relative permittivity is 4.6 at 1 MHz and 4.25 at 1 GHz with a typical tolerance of about 5%. The thickness tolerance for a 1.52 mm FR-4 laminate is quoted as ±0.152 mm, whereas microwave laminates generally have a tolerance of ±0.08 mm for the same thickness. This tolerance can translate into errors in resonant frequency for patch antennas. The machinability of FR-4

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is good, and it requires few of the special precautions required for softer PTFE based laminates. The loss tangent is usually quoted at 1 MHz as somewhere between 0.018 and 0.02. This will generally rule out this laminate for use in arrays or if gain and radiation efficiency are important considerations.

A coaxial-probe fed linearly-polarized halfwave rectangular microstrip patch antenna operating at a frequency of 2.45 GHz was fabricated on four different low-cost laminates and compared to a thicker PTFE substrate with microfiber glass loading (5870). In each case, the feedpoint was optimised for 50 Ω and the geometries were approximately square. All laminates have a 1 oz EDC cladding. The antennas were polarization matched and the gain was measured using a microwave vector network analyser, results are shown in Table 4.

Laminate	Thickness (mm)	ε_r	Measured Gain (dBi)	tan δ
5870	3.18	2.33	6.8	0.0012 (10 GHz)
4003	1.52	3.38	5.5	0.0022 (10 GHz)
3003	1.52	3.00	5.9	0.0013 (10 GHz)
GML 1000	1.52	3.05	5.8	0.003 (2.5 GHz)
FR-4	1.52	4.5	3.2	0.02 (1 MHz)

Table 4

It can be seen that the thicker PTFE/glass laminate outperforms the thinner low-cost laminates. The radiation efficiency for the 5870 (3.18 mm) is about 97 %. However, the lower cost thinner laminates perform quite well. The 4003, 3003 and GML1000 have radiation efficiencies between 86 - 91 % with gain figures better than 5.5 dBi. The high loss tangent of the FR-4 manifests itself as a significant reduction in measured gain; the radiation efficiency is only about 50 %.. The antenna fabricated on FR-4 needed to be frequency trimmed, but once the resonant length was determined, the value of dielectric constant seemed relatively stable, for the same batch.

The microstrip antenna was considered to have a narrow impedance bandwidth for many years, but more recently, the development of broadband microstrip antennas has proliferated [15]. Many different techniques have been developed including the use of parasitic elements, stacked elements and better impedance matching techniques. The wireless LAN is licensed to operate at 2.45 GHz in Europe and allocated a bandwidth of 100 MHz, which corresponds to a fractional bandwidth of 4.1%. This bandwidth is not easily achievable using single layer microstrip patches unless thick substrates are used, which increase problems with feedline reactance and radiation, and surface waves. Substrate thickness is limited to about 1.52 mm when cost is taken into account, consequently, the impedance bandwidth of the probe-fed patch antennas are too small for wireless applications. Typically, the measured bandwidth at 2.45 GHz for a patch antenna fabricated on GML1000 (1.52 mm) is 1.9 % while for 5870 (3.18 mm), it is about 3.2 %. Broadbanding techniques are necessary to achieve the required bandwidth and proximity-coupling to a buried feedline is appropriate. A design procedure for both probe-fed and two-layer proximity-coupled rectangular patches at this frequency may be found in [16]. The increase in bandwidth using proximity coupling is significant and an 8% fractional bandwidth is easily achievable. The use of a matching stub on the feedline can increase this value to about 13%. The two substrates may be bonded together using a bonding film such as Rogers 3001, Speedboard N or Polyflon film. The bonding film should be closely matched in dielectric constant to the laminate. However, thin high loss adhesive films such as FR4 prepreg, can have minimal impact on the loss performance in some applications [17].

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