DESIGN AND PRODUCTION OF LOW-COST METALLIZED POLYMER MM-WAVE COMPONENTS

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Abstract

The design and production of high precision, mm-wave waveguide components using injection molded and metallized polymers have been investigated as a possible way to reduce the cost of high volume consumer satellite terminals operating in the 20-30GHz range. Based on this experience, the issues of electrical design for molding, polymer selection, molding, and metallization are discussed as they relate to tolerances and yield, surface quality, thermal stability, and overall electrical performance of feedhorns, OMT's, and filters. The accuracy and cost limits for this approach are briefly discussed.

Motivation for component design with polymers

There are at least three important motivations for the use of metallized polymer to make mm-wave waveguide components and assemblies; a) cost-reduction, b) weight reduction, and c) improved quality.

Cost is usually an important factor for high-volume production. Metallized polymer fabrication using injection molding is a replication technology. Once the process and tooling are adjusted, it is possible to make large numbers of high-precision structures without any additional surcharge for the precision. The standard deviation of dimensions for typical waveguide structures produced in this way can be as low as 3-5µm. This allows fabrication of structures that often do not require individual adjustment or tuning which is important for reducing cost.

Weight reduction can be an important concern when one considers large structures that must be carried up a high antenna tower (e.g. tower mounted amplifiers for a cellular base station) or must be carried into space (e.g. components for satellite use). In such cases, low-weight can be more important than low-cost. The density of typical polymers is roughly half that of aluminum.

Third, we note that better fabrication quality is often possible when compared to standard machining processes. Polymer fabrication can replicate the surface of the tooling and, if it is polished, provide surfaces with lower surface impedance than surfaces created by milling. This can give lower insertion loss especially in resonant structures. Structures can be made without inside radii (commonly required in milled structures) which allows easier simulation

Applications for polymer components

As of early 2006, metallized polymer fabrication has been applied to various air-dielctric waveguide structures including slotted waveguide antennas, feedhorns, circular polarizers, orthomode transducers (OMT), and iris filters. Occasionally, polymer-dielectric structures have been demonstrated. These cover the frequency range from a few GHz to at least 42GHz. In this paper, we focus on air dielectric waveguide structures for 20-30GHz for use in a low-cost consumer satellite terminal. In this application, the waveguide structures are usually mounted outdoors near the feedhorn of the main antenna. A typical low-cost Ku band consumer satellite terminal configuration with an integrated transceiver is shown in Figure 1.

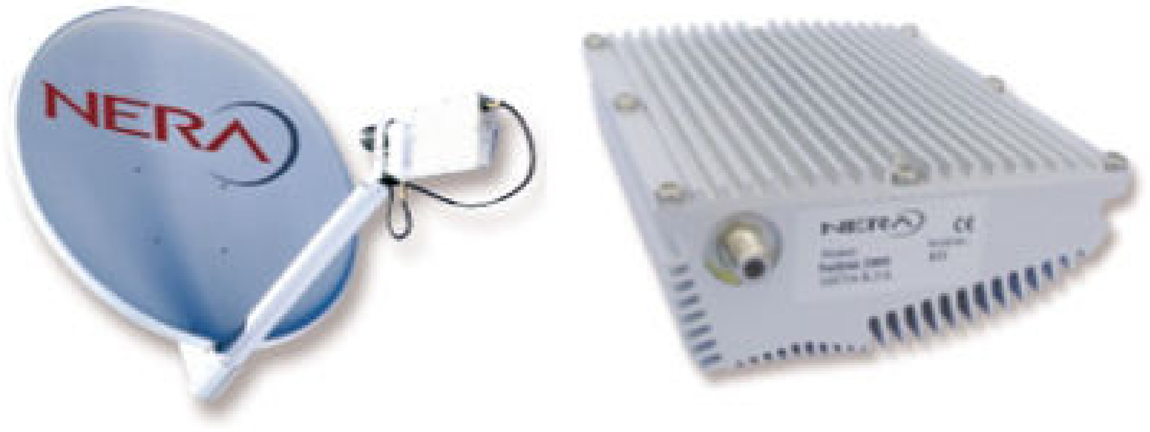

Figure 1 A typical commercial Ku band, low-cost, satellite user terminal configuration with an integrated antenna mounted transceiver.

Considerations for metallized polymer design and production

There are some special design and production considerations for waveguide structures intended for polymer injection-molding and metallization compared with fabrication by normal machining processes. In the following, we divide the design, production and evaluation process into 12 steps. We briefly describe each step and illustrate the process with a 4th order waveguide iris filter for 29.5GHz.

Step 1 - Establish clear objectives and select a production process

As with any waveguide structure, one begins with a set of electrical specifications and realistic tolerances based on a simulation tool. One also needs some mechanical (weight, strength) and thermal (operating temperature, thermal expansion limits) specifications. At this early stage it is advisable to consider the available manufacturing alternatives (machining, electroforming, EDM, etching, metal molding, polymer molding) and confirm that polymer injection molding offers the right combination of electrical performance, thermal performance, weight, unit cost, and other factors.

If metallized polymer fabrication is appropriate for the application, then one needs to select the basic production strategy. Most waveguide components must be molded in two pieces and joined later. If so, the choice of a splitting plane can have a significant effect on insertion loss and the method used to join the two parts. If the component requires an internal metal or dielectric insert, then a method for including this needs to be identified. Interfaces need to be defined such as flanges or PCB transitions. One can make a tentative selection of a polymer, surface quality specification, metallization type, and assembly method that meet the design goals at this time. In summary, it is necessary to identify all process steps appropriate for the component and confirm that they will function together to reach the objectives

Step 2 - Synthesize the Structure

An idealized structure is first synthesized with any of the normal design tools. Synthesis and optimization are usually much easier if one assumes ideal elements with sharp inside corners and ideal rectangular or circular shapes. One should remember the limitations of the molding and metallizing method chosen in step 1 and be careful to choose a structure which is compatible. For example, features with a large aspect ratio such as deep holes may be difficult to metallize with an electrolytic process but may be readily metallized with an electroless deposition process.

Step 3 – Assess Tolerances and Yield

One of the most attractive features of polymer injection molding is the high replication accuracy that can be achieved (standard deviation on the order of a few micrometers). For a given structure, the required tolerance will scale as 1/f. If one desires tuning-free fabrication, then the required tolerances should be compared with the expected molding tolerances to be sure that the tuning free yield will be sufficiently high.

There are many factors that affect the production tolerances. Among these are part size, tooling accuracy, reproducibility of source material and molding conditions, thermal control of the tooling, shrinkage factor of the material, and metallization uniformity. These factors are usually determined empirically and corrected by an iterative process.

Required tolerances are not always directly related to the tolerances of linear dimensions. For example, a broadband circular feedhorn may be relatively insensitive to a change in scale but very sensitive to deviations from the ideal circular form when cross polarization discrimination is important.

Step 4 – Add Slip Angles and Adjust the Structure

The ideal design from step 2 is usually not immediately suitable for molding. After a part is molded and cooled, it contracts around the internal features of the design and must be forcibly ejected from the tool. In order to remove the part from the mold tooling without damage, a small slip angle (typically 1-3 degrees) is required on all surfaces parallel to the ejection direction. Slip angles may be avoided on some external surfaces by using a more complicated tool design but with a significant increase in tooling costs. The addition of these angles to the design will usually affect the electrical performance and the design must be re-optimized. This usually requires the use of a full-wave 3D simulation tool.

If insertion loss is important in the structure, it is usually most efficient to first re-optimize the structure using perfect electrical conductors (PEC) as boundaries and then add a realistic surface conductivity to the adjusted structure to calculate insertion loss. It is important to remember that the bulk conductivity of the metallization is usually not relevant. Surface conductivity at GHz frequencies is strongly affected by surface roughness and can be surprisingly low. Critical surfaces, especially in resonators, should be polished in the mold (even though this adds to the tooling costs) and one should use a polymer that is capable of replicating that polished surface. Generally, it is necessary to achieve an RMS surface roughness of less than 1μm to obtain the lowest possible insertion loss. To achieve such good surfaces also requires a metal-polymer combination which does not rely on surface roughness for good adhesion.

Step 5 – Select a Polymer

There is an enormous range of polymers available today and some strategy is required to find an optimal solution. For air-filled waveguide structures, the polymer is only a mechanical support for the metallzation and therefore its mechanical properties are most important. Space does not permit a discussion of the selection process. We note only that over the last few years, two types of polymers have become prominent; those based on liquid-crystal polymers (LCP) and those based on polyetherimide (PEI) polymers. Both can tolerate the relatively high temperatures needed for electronic assembly with soldering.

For many waveguide structures (especially filters), thermal stability is a major concern. This is related to the coefficient of linear thermal expansion (CLTE) of the material. Usually a polymer by itself has a relatively high CLTE. Polymers are often filled with some material which lowers CLTE, lowers cost, and increases mechanical strength. The type of filling and its behaviour during molding determines whether the molded structure is thermally isotropic or not. The performance of a metallized polymer structure is often compared with that of a machined aluminum structure. It is desirable to select a polymer with an isotropic CLTE equal to or slightly less than aluminum. If so, then the CLTE is also compatible with the metallization.

Some other requirements are that a) the polymer should be able to replicate the surface of a polished mold and produce surfaces with less than 1μm RMS roughness, b) the material should be strong enough for the selected assembly method, c) should limit water absorption when humidity is present, d) long term creep must be sufficiently low especially for parts under stress, and e) the cost should be acceptable. It is important to remember that datasheet values are only nominal and one must determine actual polymer properties from component measurements.

Step 6 – Select a Metallization Process

There are many factors that affect the choice of a metallization process including conductivity, skin depth, thermal expansion coefficient, surface adhesion to the chosen polymer, aspect ratio, and degradation over time. The three main options for metallization are physical vapor deposition (PVD), electrolytic deposition, and electroless deposition.

PVD is very low cost but the parts are exposed to high temperatures and there is the possibility of distortion. It is only useful for low-aspect ratio structures since the metal thickness varies with the angle of incidence. It is most often used to apply aluminum or copper. Electrolytic deposition is done at low temperature and is suitable for the application of relative thick layers of copper or silver. High aspect ratio structures can be metallized with special electrodes but this adds to the cost. There will usually be some variation of metal thickness on a part with complex geometry. Electroless deposition is relatively expensive but has the advantage that it can provide a uniform layer of metal on even very complex surfaces. It is often used to provide a final layer of silver over an underlying thicker structural layer of copper.

Silver has the highest conductivity of all metals and is relatively robust against corrosion as long as the surface is protected against sulfur bearing compounds. A uniform silver layer or a combination of copper and silver which is a few micrometers thick is adequate for most applications above 10GHz. Protective coatings are problematic for microwave performance and add cost and are usually not necessary unless the environment requires it.

Step 7 – Select a Mechanical Design and Assembly Method

The mechanical design includes the choice of a splitting plane and an alignment method for assembly. The same structure can be made with different locations for the splitting plane as shown in Figure 2. The mid E-plane split design shown in Fig. 2a has potentially lower losses with an imperfect contact since less current must cross the junction. The mid H-plane split design in Fig. 2b has potentially higher losses but has a lower aspect ratio and is thus easier to metallize. Both mid E-plane split and mid H-plane split designs require alignment structures to insure that the irises are properly aligned after assembly. In contrast, the top H-plane split design shown in Fig. 2c only requires a flat top to complete the structure and thus no alignment structure is required. This removes one possible source of error but the top H-plane split structure has the largest aspect ratio. In our experience, there is no significant practical disadvantage with the mid H-plane split filter over the mid E-plane split design and both are possible options..

In general, we try to use symmetry as much as possible to reduce tooling costs. In Fig. 2a and 2b the structures are symmetrical so that two identical molded parts are used to form the complete structure. The alignment structure is kinematic so that the two halves are self-aligning and there is only one possible way to assemble them.

The contact surfaces between the two parts of the waveguide must be flat and normal to make a good contact. In this example, we used an external clamp to hold the two pieces together but they could have been assembled with screws, soldering, or other methods. Additional stiffening ribs (not shown in the figure) on the back of the structure maintain the waveguide dimensions and provide stability during and after assembly.

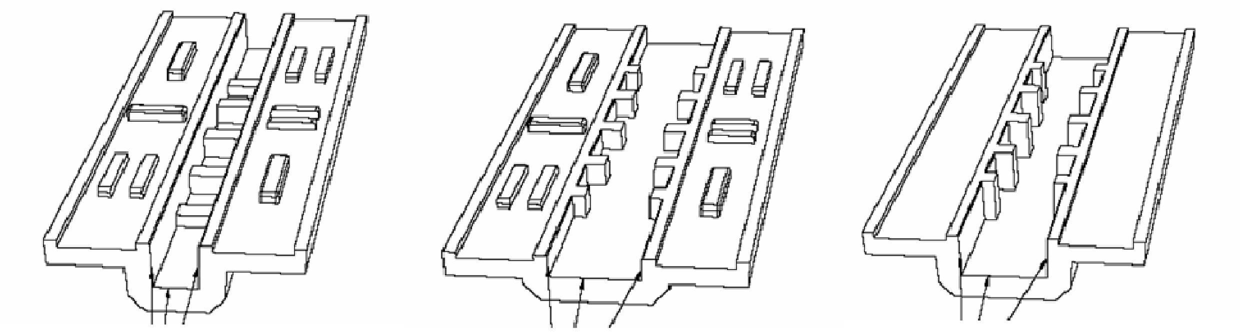

Figure 2 Three options for fabrication of the same waveguide filter; a) mid E-plane split, b) mid H-plane split, and c) top H-plane split.

Step 8 – Adjust the Design for Production

After the electrical and mechanical design are finished and we have selected a polymer and metallization method, there remain a few adjustments that need to be made to the design prior to production. First, the tooling design must be compensated for the metal thickness which is often on the order of 10-15μm thick. Second, the design should be biased so that mold tuning will involve metal removal (which is much easier) rather than metal addition. Third, all surfaces that need to be polished should be identified at this time.

Step 9 – Moldflow Analysis

An essential step in tool design is moldflow analysis. This is a computer simulation of the way that the mold is filled with the molten polymer. This necessarily involves the selection of the number, size and location of the “gates” (the openings where molten polymer enters the mold). The simulation identifies the locations where flow fronts come together to form “weld lines” and where air can be trapped in blind holes which can prevent proper mold filling. The simulation can also predict part warpage after cooling. Generally, higher mold temperatures, faster injection, and higher injection pressure will improve molding accuracy and reproducibility and these can be quantified with this simulation. We do not recommend investing in tooling or trying to make waveguide structures without moldflow simulation.

An example of a molding defect due to weldlines on an iris in the mid E-plane split filter from Fig. 2a is shown in Fig. 3. The iris height deviated from the design value by 75-120μm in this case which was enough to destroy the operation of the filter.

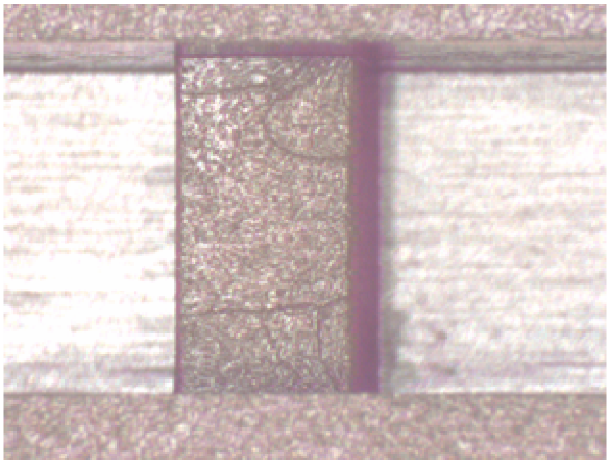

Figure 3 Molding defect (weld lines) on an iris in an mid E-plane split filter due to improper mold filling

Step 10 - Tooling Design and Fabrication

The most important issues with tool design are surface quality, cooling, ejection, and hardening. Close cooperation with the toolmaker is necessary because the toolmaker will likely have little awareness of how tooling decisions can affect microwave performance. Surface quality is a key issue as explained earlier. Microblasting can be used to achieve tool surfaces with roughness on the order of 1μm RMS but a more demanding requirement will require polishing the mold and this can add significant cost. Therefore the surface quality specification should be good enough but not excessive. So called ‘cooling’ of the tooling (which is actually temperature control of the tool) should be discussed with the toolmaker since non-uniform cooling will be reflected in part distortions. The ejection pins must be placed where they will not affect the critical waveguide surfaces since there is always some marking of the surface. Finally, hardening of the tooling should be considered only after the mold has been adjusted and is ready for production since it is very difficult to machine the hardened steel.

Step 11 – Pre-production

Once the tooling has been produced, it must be verified with full and partial test shots at various mold temperature, melt temperature, injection pressure, and cycle time values to find the best operating point. This may already be known to the molder if they have experience with the particular polymer. Partial shots are used to understand any filling problems that might remain. The test parts should be inspected for any damage during ejection (e.g. from the ejector pins or from insufficient slip angles). Once the process is stabilized, one should make a short run of a few hundred pieces and make detailed mechanical measurements on them. For each measurement, one can calculate a mean dimension and a standard deviation. The mean dimension is compared with the design value (corrected for metal thickness) to determine the correction needed in the tool. The standard deviation provides a measure of the process reproducibility.

The surface properties of the polymer should be checked in the critical waveguide areas. A few pieces should also be metallized and the surface properties of the metal measured. X-ray measurements can confirm the thickness and composition of the metallization. If one has not previously used the particular combination of polymer and metallization, the adhesion should also be confirmed with a mechanical pull off test.

Finally, some parts should be assembled into working units and tested electrically as appropriate for the structure. Filters should be tested over the intended temperature range of use and any frequency deviation noted. This can provide an independent confirmation of the CLTE as well as provide a sensitive test for molding accuracy. The polarization dependent performance of linear-to-circular polarizers and feedhorns provides an even more sensitive test of accuracy. The electrical measurements should be correlated with the mechanical deviations using a full wave simulator to make sure that the reason for any deviations is understood. If any further tool corrections are needed, they should be done.

Step 12 – Production and Testing

When everything is adjusted properly and performance is confirmed, then it is time to begin mass production. A hardened tool should be capable of producing roughly 500K parts before wear on the tool requires renewal. A few parts should be tested at regular intervals to insure that the process is stable.

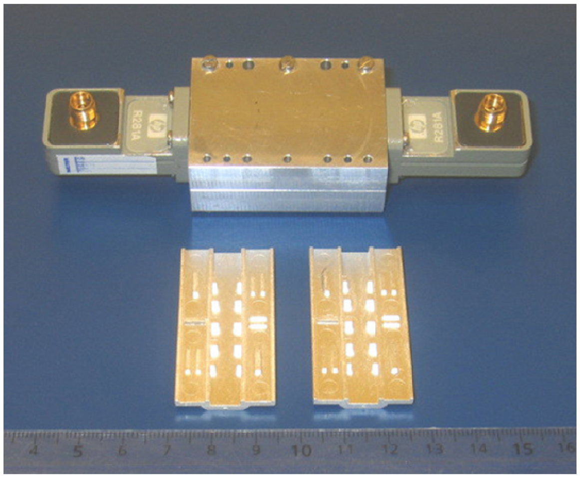

Figure 4 A four pole bandpass waveguide iris filter for 29.5 GHz with a mid H-plane split and metallized with silver. The two sides are held together with a mechanical clamp.

To illustrate what is possible, we show some results for a 4 pole waveguide bandpass filter made with polyetherimide polymer and metallized with electrolytic copper plus a final layer of silver. The S21 response of the filter was measured and compared with the design values. There was good agreement and the filter met all requirements without any adjustment of the filter or the tooling. This is considered "tuning free" production.

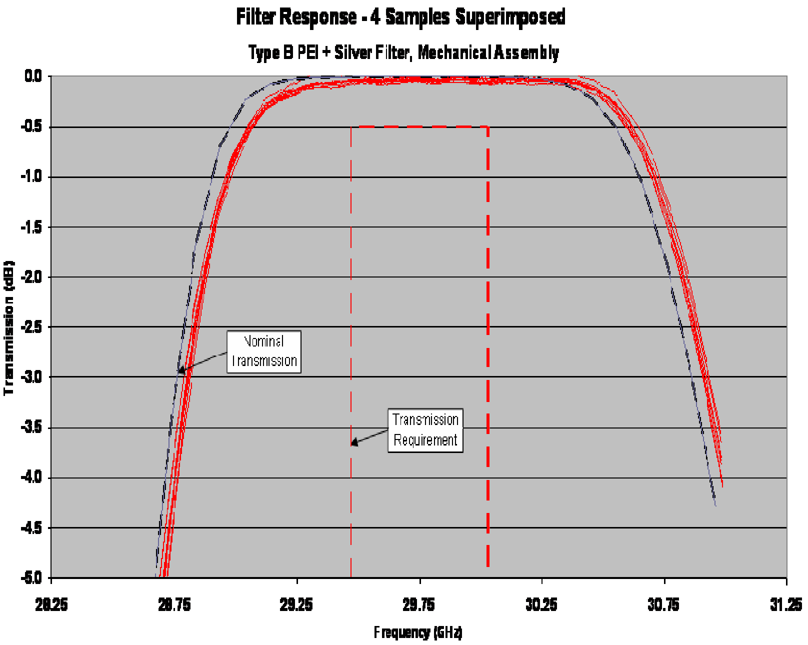

Figure 5 The measured S_{21} response of the metallized polymer filter compared with the design. The insertion loss was much less than -0.5dB and there was a small frequency shift.

Conclusions

We conclude from this work that it is possible to produce low-cost, metallized polymer microwave and mm-wave components with absolute tolerances < ±10μm and with standard deviation of individual dimensions about 2-3μm. For the specific part shown here, these tolerances were sufficient that no mold or part tuning was required for use at 20-30GHz. If larger systematic errors occur, they can be removed by adjusting the tooling. The insertion loss was quite low due to low effective surface resistance even with an H-plane split. The alignment structures functioned very well. The cost to fabricate this kind molded waveguide structure seems to be so low that the dominant cost is now the metallization (e.g. cost of the silver). The upper frequency limit for such devices depends on the function of course, be we believe that applications up to 100GHz are possible.

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