

Planar Transmission Line Technologies

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Abstract

Characterization of the cosmic microwave background polarization will ultimately require both a large number of cooled background limited detector elements and precise control of instrument systematics. To this end, bolometric sensors with passive circuit elements integrated on a chip form an attractive technology owing in part to the technological approach's flexibility, relatively compact footprint, and compatibility with other sensor fabrication steps. Such circuits will enable polarization separation and signal band definition to be done on a single device with the required control over the response while making efficient use of the focal plane area. In this white paper, we review the current status of the superconducting planar circuits as they relate to millimeter wave polarimeters for space borne applications.

1. Introduction

The next generation of instruments used in the characterization of the radiation properties of the Cosmic Microwave Background (CMB) will necessitate large numbers of background-limited sensors with well defined beams to achieve the required system sensitivity and systematic control. In this limit, focal plane area will be an extremely valuable commodity in a space-based platform. In populating the instrument's focal plane with high performance and reliable detector technologies, near ideal performance from the elements used in realizing the sensor response is highly desirable.

Historically, a variety of circuit technologies (e.g., lumped element components, planar transmission structures, waveguides, and quasi-optical devices) have been used in precision millimeter wave photometric sensors. Given the precision photolithographic thin film and micromachining processes used in making the present generation of bolometric detectors, a variety of other circuit elements are naturally compatible with the existing fabrication requirements. In adding such elements to the sensor, one strives to improve functionality and reduce hand assembly operations while maintaining overall reliability and yield. For large arrays of millimeter wave sensors the integration of superconducting and normal metal planar-transmission-line-structures are commensurate with these general design objects.

2. Technical Description

2.1 Transmission Line Elements

Planar transmission line structures can be realized in many forms (Matthaei, et al., 1964; Bahl, et al., 1996; Chang, et al., 2002). Cross sections of representative examples in common use are shown in Figure 1. These include microstrip, co-planar waveguide, slotline and parallel-plate

planar transmission lines. Each topology is characterized by the modal distribution of its fields, as well as achievable levels of characteristic impedance, phase velocity, and number of modes supported by the structure. Combinations of the elements from this pallet can be used to produce such circuit elements as delay lines, crossovers, resonators, transitions, power combiners, and filters. Perhaps more importantly, well established strategies exist for their design, analysis, and general circuit implementation. With the addition of normal metals; terminations and broadband absorbers can also be realized and used to tailor the circuit response as necessitated by the end application.

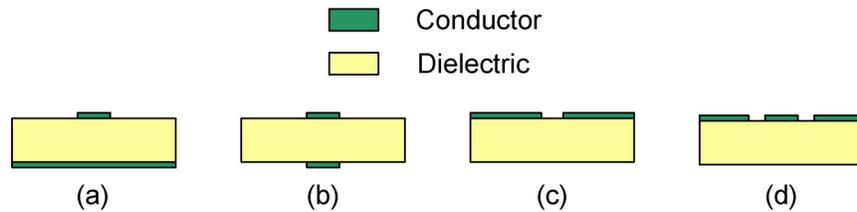


Figure. 1. The cross-section view of four commonly employed planar transmission lines structures: (a) microstrip, (b) parallel plate line, (c) slotline, and (d) co-planar waveguide.

An understanding of behavior and relationships between these structures can enable the creation of high performance passive circuit elements. The fields in the microstrip topology can be relatively well-confined for large line width over substrate height ratios and is well suited for realizing elements with low characteristic impedance and radiation loss. Slotline on the other hand, which to a good approximation is the electromagnetic complement to the microstrip configuration, has poor field confinement and can be susceptible to radiative loss. The underlying (complementary) symmetry between slotline and microstrip transmission line topologies can be utilized in realizing broad band antenna feed elements and 180 degree phase inversions for example. In the limit the lower metal ground plane region in microstrip shrinks to the width of the upper line, the relatively high impedance parallel plate transmission line structure is formed. Finally, co-planar waveguide (CPW) architectures are possible. In possessing three conductors, this medium supports two modes of propagation. These modal field distributions can be characterized by their even and odd spatial symmetries. The existence of these two differing modes can be exercised from a design perspective to create a rich variety of coupling structures and hybrids. Alternatively, one mode can be intentionally suppressed in order to insure single-mode propagation on the structure. This can be done for example with an “airbridge” connecting the two outer conductors which effectively shorts out one of the two modes. Topologically this configuration is very similar to microstrip with a slot in the ground plane. With appropriate care, this relationship can be used in creating microstrip lines structures with higher characteristic impedance levels if needed.

2.2 Lumped verses Distributed Circuit Elements

Transmission line structures which approximate lumped circuit elements are a conceptually helpful starting point to see how various design functions can be realized. For example, by using an electrically short section of low impedance line, an element which approximates a capacitor can be made. Similarly, a high impedance section with electrical delay less than $\sim\pi/4$ can approximate an inductor. In synthesizing circuit elements in this manner, the

implicit symmetries of a lumped circuit element – namely that the structure only has a single mode of propagation and length scales characterizing the element are small compared to a wavelength – must be respected over the required design band. Stated another way a simple lumped circuit element can be characterized by a single parameter. A transmission line on the other hand is characterized by two or more parameters (i.e., its characteristic impedance, propagation velocity, and physical length). Such differences in dimensionality between idealized and physically achievable components can lead to a breakdown in applicability of simple circuit based synthesis approaches. In this limit, transmission line models and full wave analysis approaches are required to simulate the response. An iterative analysis scheme is typically followed in order to capture potential issues early in the design process. In practice, the required fabrication tolerances required by lumped element designs can potentially lead to challenges in terms of component performance and yield.

Alternately, by changing the characteristic impedance, phase velocity, and mode shape of the guiding structure on length scales small compared to the wavelength in the transmission media, adiabatic mode transformers can be realized. In this manner one can achieve responses over inherently large bandwidths which can be quite insensitive to fabrication tolerances. For cryogenic millimeter applications this approach is preferable from a yield perspective when compatible with available space and the desired circuit functionality. Between these two limiting cases, the use of delay lines and steps in impedance contrast between line sections can be used. The resonant sections formed by these circuit topologies for example can be cascaded and tailored to form blocking, high-, low-, and band-pass filters. The primary challenge in this approach is achieving adequate control over the spurious higher order circuit responses over the design band set by the application. See Figure 2 for an example of this behavior which can be found in commonly available commercial filter designs. The filtering requirements of incoherent detectors are more stringent than their coherent counterparts which have in-band signal gain. However, these filtering needs are achievable in practice.

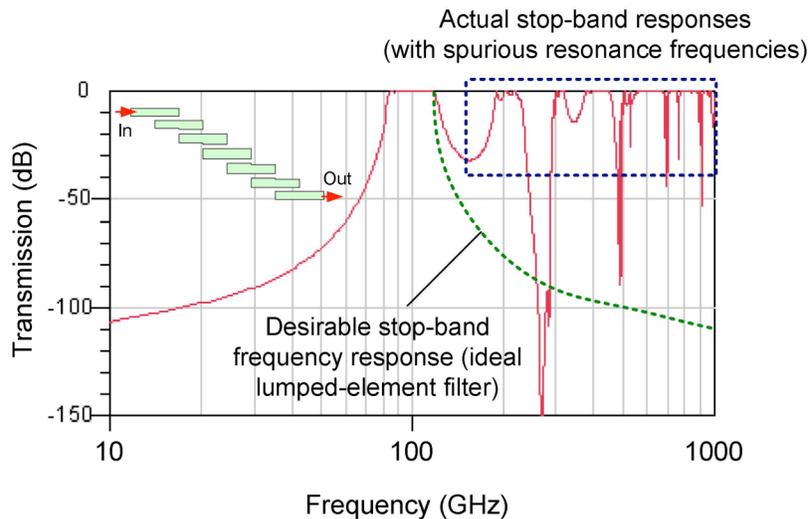


Figure 2. The frequency response of a conventional half-wave coupled line band-pass filter (red solid line) at 100 GHz is compared to its idealized lumped-element band-pass counterpart (green dashed line). The high frequency coupled line filter’s deviation from the ideal lumped element response in the coupled line filter can arise from inadequate control over resonances in the individual filter sections.

3. Material Consideration Overview

In choosing a metallization system for the planar transmission line one would ideally like to simultaneously achieve the following properties: 1) single-mode operation over the waveband of interest, 2) losses associated with the metallization and spurious radiation subdominant to the dielectric losses in the substrate, and 3) the characteristic size scale of the circuit elements compatible with photolithograph fabrication and interface to the thermal detector at the operational temperature. One finds that only superconducting metal systems with transition frequencies above the highest CMB science band of interest are unable to meet these needs. The properties of these materials above their superconducting transition can provide a natural high frequency attenuation cutoff for definition of the CMB signal band. For example, for niobium on thin film dielectrics incident radiation above $\sim 700\text{GHz}$ is highly attenuated by the transmission line structures.

For thin film substrates at millimeter wave frequencies, the kinetic inductance factor should be incorporated into the microstrip model to accurately model the propagation constant and the impedance of the microstrip lines (Yassin and Withington, 1995). Kinetic inductance is a function of temperature, thickness (t), critical temperature (T_c) and penetration depth (λ_L) of the superconductor. This effect can be modeled as a sheet inductance (Kerr, 1999) in the microstrip line as shown in Figure 3. In order to make the kinetic inductance subdominant and reduce the overall sensitivity to fabrication of passive circuit elements, the ratio t/λ_L needs to be greater than a few and the physical temperature of the physical lines needs to be maintained significantly below the critical temperature. These design desires are readily achievable in practice and means of modeling these electromagnetic effects are well developed.

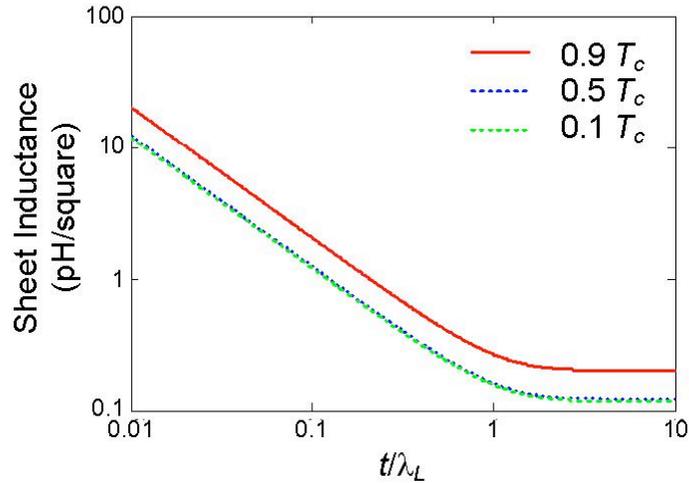


Figure 3. The kinetic inductance of the superconducting niobium as a function of thickness over penetration depth (t/λ_L) is presented for three temperatures.

Given a metallization choice, the quality of dielectric material essentially sets the achievable loss in the transmission line structure. Dielectric materials that have low loss, are compatible with the processing demands of the detector, stable, and have controllable material and dimensional properties are necessary to meet the application demands. Thin-film substrates such as SiO_x , Silicon Nitride, Al_2O_3 , as well as mono-crystalline silicon layers have been

explored in this context. A knowledge and control over the substrate’s dielectric constant real and imaginary components is key to producing delay line elements (e.g., filters, phase shifters, and hybrids) with predictable performance. Investigations of the properties of SiO_x (Vayonakis, et al., 2002) have revealed a dielectric dominated loss of ~0.5% per wavelength at ~3 millimeters. Additional studies of uniformity of these parameters across the wafer will be required to understand the yield of circuit elements whose response is dependent upon transmission line propagation delays.

The dimensions of the transmission line structures must also be considered in the design. To maintain single-mode operation it is important to prevent the excitation and propagation of surface wave modes. The surface wave propagation frequency (f_s) is a function of thickness (h) and relative dielectric constant (ϵ_r) as shown in Figure 4, where c is the speed of light. The deleterious effects of surface waves can be suppressed by using a thin substrate and operating the circuit significantly lower than the onset of surface wave propagation. In addition, radiative losses can be a design concern that can be controlled by ensuring the ratio of the substrate thickness over the guide wavelength is small compared to unity (Hoffmann, 1987). Minimizing the number of discontinuities in the circuit can also help in controlling spurious radiation. Care should be exercised in designing slots or electrically large structures. The minimum single-mode operating wavelength is set by substrate and line dimensions. For microstrip the onset of the next mode occurs at a wavelength corresponding to approximately twice the electrical width of the line. In practice this consideration sets the lowest characteristic impedance level available to the designer. The highest impedance scale is set by the minimum repeatable fabrication line width. In practice, an impedance contrast greater than ~5 is readily achievable and commensurate with the application circuit demands.

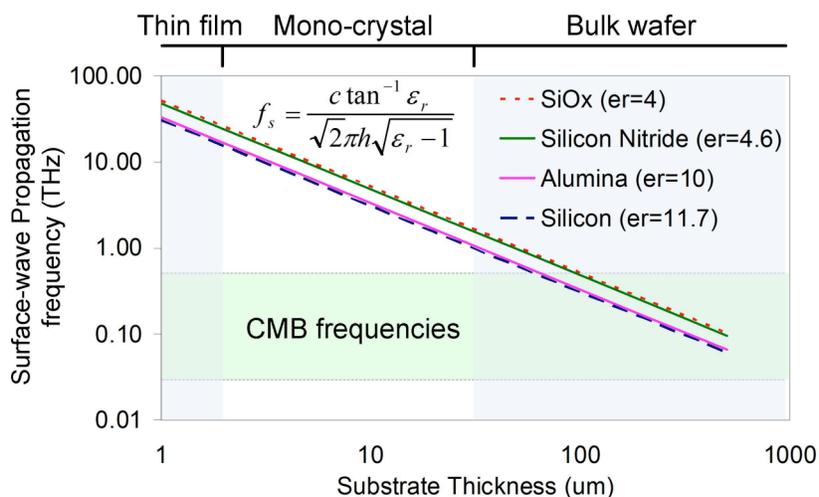


Figure 4. The surface-wave propagation frequency for different substrates as a function of substrate thickness. Substrate technologies presently under investigation are compatible with the frequency range of interest for supporting CMB polarization applications.

The presence of a microstrip ground plane can provide a natural separation between the microwave, bias, and readout signals. Thus it provides a popular architecture for achieving the various sensor circuit demands. This stated, other transmission line structure architectures are

also commonly employed as circuit elements within the planar circuit to achieve appropriate impedance contrast and levels to produce the desired sensor performance.

4. Planar Transmission Lines Technology Benefits and Disadvantages

4.1. Benefits

- Planar transmission line structures are compatible with integration on a detector chip while maintaining high optical coupling efficiency. Their compact size allows efficient use of focal plane area. Given photolithographic and process tolerances this approach provides a means to produce parts with high repeatability, yield and low process variation.
- Single-mode transmission line structures are able to cleanly prevent the occurrence of and provide control over several potential optical and frequency dependent systematic effects which can have a negative impact on system calibration and imaging performance. In particular, single-mode filters will be able to prevent ghost images due to multiple reflections and suppress the inherent frequency dependence of the filter pass band with scan and acceptance angles (Macleod, 2001) which can be encountered in quasi-optical filters.
- Issues related to the uniformity of planar filter structure temperature are subdominant to detector cooling and stability requirements. This is not the case for quasi-optical filtering approaches where control over infrared blocking must be achieved in order to prevent thermal heating of central regions of the filter stack (Ade et al., 2006).
- Above the superconducting gap frequency and below the onset of multimode propagation in the structure the relatively high ohmic loss in the normal metal state can be used in absorbing and thus limiting the out of band power presented to the detector.
- Required synthesis, transmission modeling, and electromagnetic simulation design tools presently at relatively mature levels.

4.2. Disadvantages

- The geometries and materials used in single-mode filters can require tighter and greater control over process tolerances (relative to their quasi-optical counterparts) to insure desired operational performance.
- Care must be taken in the overall design not to allow supporting circuitry to drive sensor fabrication and test complexity/risk.
- Each single-mode transmission line channel experiences an independent filter which must be characterized in flight.
- Cryogenic array characterization and screening capabilities presently at relatively low level of maturity.

5. Technological Readiness Level (TRL) Assessment

In order to assess the technical readiness of planar transmission line technologies, we consider microstrip filters as a representative example. Of the required elements for this

application, definition of the sensor pass-band presents the most challenging technical fabrication and design challenge for the use of transmission line structures on the sensor chip. Examples of planar filters studied by various groups to date include: (1) via-less 3rd order Chebyshev LC filter synthesized from CPW inductors and microstrip stub capacitors integrated with a planar slotline antenna array (Kuo, et al., 2006), (2) quarter-wave microstrip combline filters integrated with a double-slot dipole antenna array (Myers et al., 2008) which in its prototype form has demonstrated an in-band filter transmission efficiency of $\sim 73\%$, and (3) a superconducting planar stepped-impedance low-pass filter used in conjunction with a cutoff waveguide antenna coupling structure to define the signal pass-band (Stevenson et al., 2008). At this time appropriate control over the normal metal system used in realizing microwave termination, attenuators, and detector absorbers has been demonstrated.

Prototype variants on the required passive circuit elements (e.g., transmission line structures, filters, bias chokes, etc.) to support CMB polarization science requirements will reach (and in some cases have arguably reached) TRL five under the on going funding cycle. However, one cautions that further support will be required to produce optimal designs and field these elements in fully integrated systems. Further design and fabrication iterations will also be required to validate fully testable structures with acceptable levels of yield and reliability. Demonstration of these elements of technical maturity will be a key to mitigation of mission cost and risk.

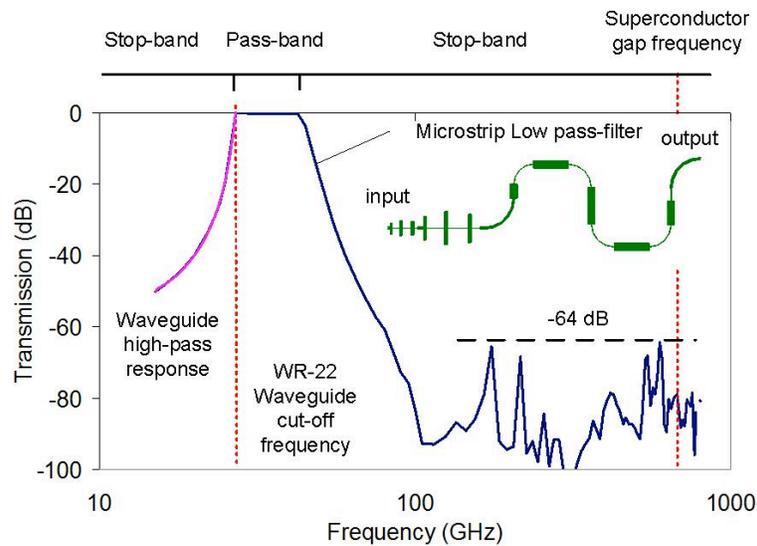


Figure 5. Simulated frequency responses of the band-pass filter consisting of waveguide interface and microstrip low-pass filter with ultra-wide stop-band responses. The physical representation of the filter is shown on the right hand side (Stevenson et al., 2008).

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