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The Continuous Transverse Stub (CTS) Array: Basic Theory, Experiment, and Application

W. W. Milroy
Hughes Aircraft Company
Radar Systems Group

Abstract

A new microwave coupling/radiating element, the Continuous Transverse Stub (CTS) is introduced. The basic theory and application of this element in antenna arrays, filters, and couplers are described. Performance, producibility, and packaging advantages relative to competing technologies are enumerated. Prototype antenna array designs, hardware, and measurements at Ku- and V-band are described.

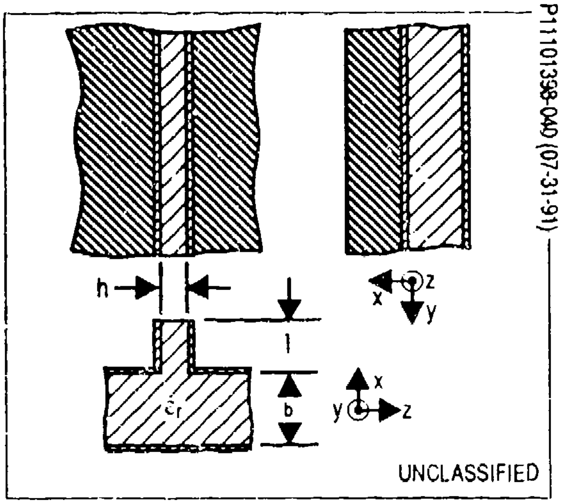
Introduction

ontinuous transverse stub (CTS) residing in one or both conductive plates of a parallel plate waveguide may utilized as a reactive or radiating element in microwave, millimeter-wave, and quasi-optical filter and enna applications. Purely reactive elements are realized through conductively terminating or narrowing the of the stub. Radiating elements are formed when stubs of moderate height are opened to freespace. Precise ntrol of element coupling or amplitude and phase excitation via coupling of the parallel plate waveguide des is accomplished through variation of longitudinal stub length, stub height, parallel plate separation, d the constituent properties of the parallel plate and stub dielectric medium(s).

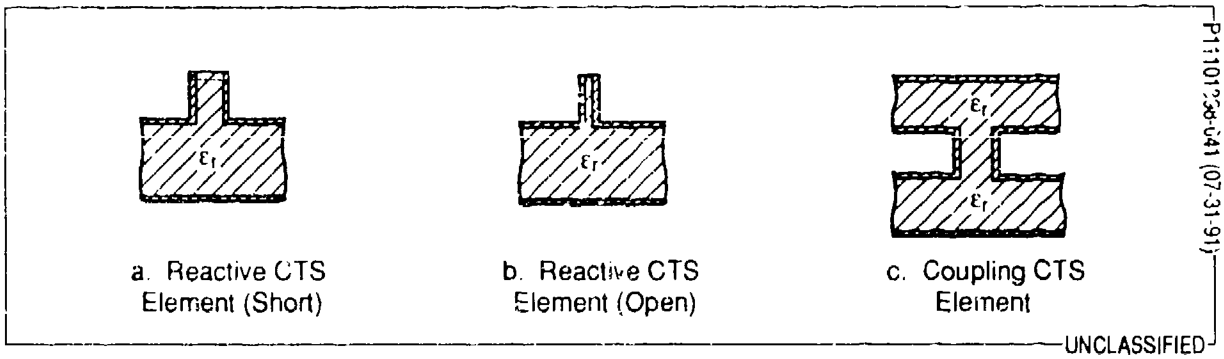
e CTS element can be arrayed to form a planar aperture or structure of arbitrary area, comprised of a linear rray of continuous transverse elements fed by an arbitrary line source. Conventional methods of coupler, lter, or antenna array synthesis and analysis can be used in either the frequency or spatial domains.

.0 Basic Theory

igure 1 illustrates the basic CTS element. Incident waveguide modes, launched via a primary line feed of rbitrary configuration, have associated with them longitudinal electric current components which are interrupted by the presence of a continuous or quasi-continuous transverse stub, thereby exciting a longitudinal, z-directed displacement current across the stub/parallel plate interface. This induced displacement current in turn excites equivalent x-traveling waveguide modes in the stub which travel to its terminus and either radiate into freespace, are coupled to a second parallel plate region, or are totally reflected.



(U) Figure 1. Radiating CTS Element



(U) Figure 2. CTS Element Configurations

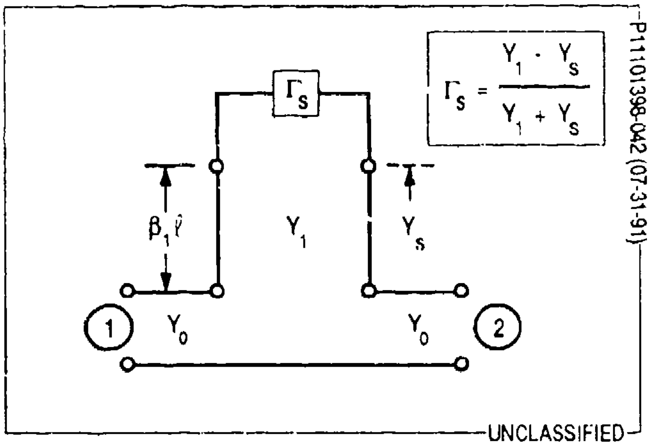
For the radiator case, the electric field vector is linearly oriented transverse to the CTS element. Radiating, coupling, or reactive CTS elements can be combined in a common parallel plate structure to form a variety of microwave, millimeter-wave, and quasi-optical components including integrated filters, couplers, and antenna arrays. Figure 2 shows the basic CTS element in its short-circuit, open-circuit, and coupler configurations.

Backscattered energy from both the parallel plate/stub and stub/freespace or stub/secondary guide interfaces coherently interact with incident energy in the conventional transmission line sense as shown in Figure 3. These basic interactions are adequately modeled and exploited using standard transmission line theory. Fringing effects at both interfaces are adequately modeled using conventional mode matching techniques and/or two-dimensional finite element analysis. The variable length (l) and height (h) of the coupling stub controls its electrical line length ($B_1 l$) and characteristic admittance (Y_1) and allows for controlled transformation of its terminal admittance (dependent primarily on h, e_r, and external mutual coupling effects) back to the main parallel plate transmission line, whose characteristic admittance is governed by its height, b, thus allowing for a wide range of discrete coupling values, $|K|^2$ from -3 dB to less than -35 dB. Variations in coupling stub length also allow for straightforward phase modulation of the coupled energy, as required in shaped beam antenna and multistage filter applications.

Figure 4 shows the derived scattering parameters (S_{11},S_{22},S_{12},S_{21}) and coupling coefficient, $|K|^2$, for the CTS element based on simple transmission line theory (neglecting fringing effects.) Note that coupling values are chiefly dependent on the mechanical ratio of stub height (h) relative to the height (b) of the parallel plate waveguide region, consistent with a simple voltage divider relationship. Because this mechanical ratio is independent of the operating frequency and dielectric constant of the structure, the CTS element is inherently broadband and forgiving of small variations in mechanical and constituent material specifications. Y_s may be set to infinity, zero, or Y_2 configurations without loss of generality. Note that the two-dimensional, semi-infinite, non-resonant nature of the CTS structure lends itself well to relatively simple finite-element and mode-matching analyses.

Based on the simple transmission-line model and assuming an isolated element, parameterized coupling curves for radiating element coupling versus stub height (h) may be computed for the purpose of sensitivity analysis. Figure 5 illustrates a nominal coupling curve (solid) for an element intended for operation at 60 GHz. Note the benign effect of frequency, dielectric constant, stub height, and parallel-plate separation variation on predicted coupling values (dash).

As an overmoded structure, the parallel plate transmission line within which the CTS elements reside will support a number of waveguide modes which simultaneously meet the boundary conditions imposed by the two conducting plates of the structure. The number and relative intensity of these propagating modes depends



(U) Figure 3. Simplified Equivalent Circuit

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$$\hat{S}_{11} = \hat{S}_{22} = \frac{\alpha}{(1+\alpha)} \qquad \hat{S}_{12} = \hat{S}_{21} = \frac{1}{(1+\alpha)}$$

$$|K|^2 = 1 - \frac{\left|1+|\alpha|\right|^2}{|1+\alpha|^2}$$

<u>WHERE:</u>

$$\alpha = \left(\frac{h}{2b}\right)\left[\frac{1+\Gamma_{se}{}^{-j2\beta_1 l}}{1-\Gamma_{se}{}^{-j2\beta_1 l}}\right]$$

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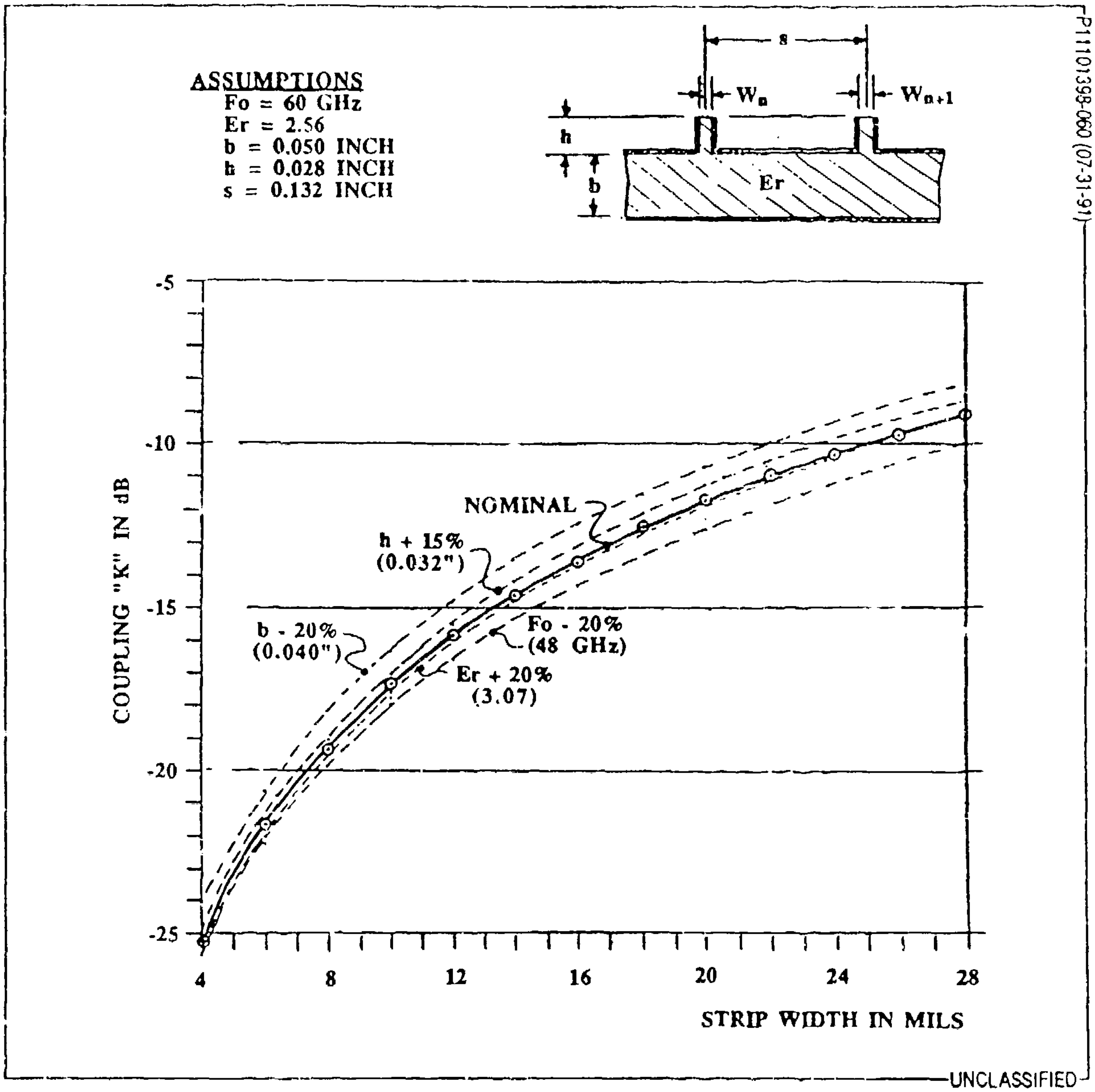
(U) Figure 4. Equivalent Circuit Design Equations



(U) Figure 5. Sensitivity Analysis of CTS Coupling Factor Versus Key Design Parameters exclusively upon the transverse excitation function imposed by the finite line source. Once excited, these mode coefficients are unmodified by the presence of the CTS element because of its continuous nature in the transverse plane.

In theory, each mode has associated with it a unique propagation velocity which, given enough distance, will cause undesirable dispersive variation of the line source imposed excitation function in the longitudinal direction of propagation. However, for typical excitation functions, these mode velocities differ from that of the dominant TEM mode by much less than one percent and the transverse plane excitation imposed by the line source is therefore essentially translated, without modification, over the entire finite longitudinal extent of the CTS array structure.

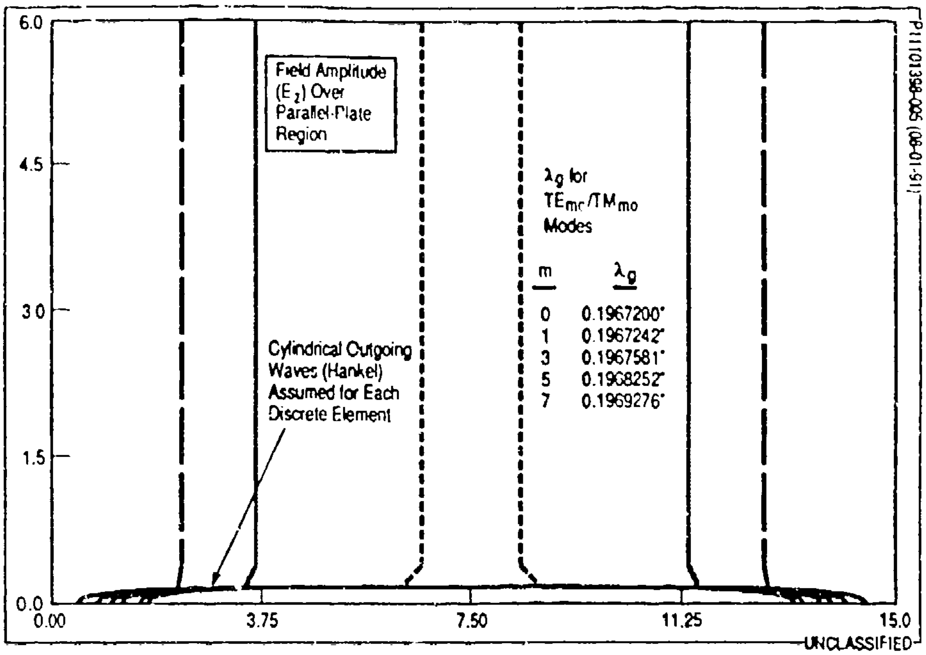
Figure 6 illustrates the theoretical constant amplitude contours for the x-directed electric field within an air filled 6 by 15 inch parallel plate region fed by a discrete linear array located at y=0 and radiating at a frequency of 60 GHz. A cosine-squared amplitude excitation was chosen so as to excite a multitude of odd modes within the parallel plate region. Note the consistency of the imposed transverse excitation over the entire longitudinal extent of the cavity.

The relative importance of edge effects in the CTS array depends primarily on the imposed line source excitation function, but they are generally small because of the strict longitudinal direction of propagation in the structure. In many cases, especially those employing steep excitation tapers, short circuits may be introduced at the edge boundaries with little effect on internal field distributions. In those applications where edge effects are not negligible, load materials may be applied as required at the array edges.

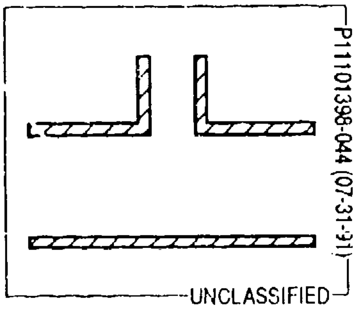
3.0 Relative Advantages

For antenna applications, a CTS array realized as a conductively plated dielectric has many performance, producibility, and application advantages over conventional slotted waveguide array, printed patch array, and reflector/lens antenna approaches. Some distinct advantages in filter and coupler applications may be realized as well.

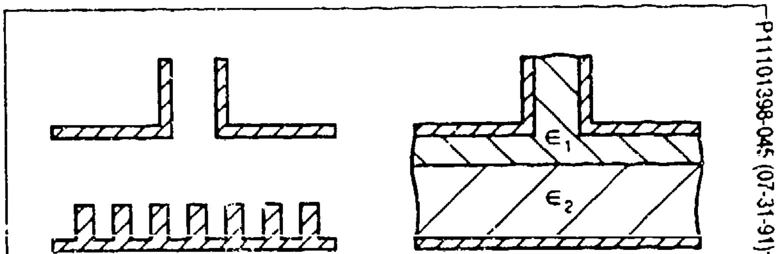
The CTS technology is applicable to all planar array applications at microwave, millimeter-wave, and quasi-optical frequencies. Shaped beams, multiple beams, dual-polarization, dual-bands, and monopulse functions can be accommodated. In addition, the planar CTS array is a prime candidate to replace reflector and lens antennas in applications for which planar arrays have proved inappropriate because of traditional bandwidth or cost limitations.



(U) Figure 6. Constant Amplitude Contours in CTS Parallel Plate Region



(U) Figure 7. Air-Filled CTS Element



(U) a. Artificial Dielectric CTS Element

(U) b. Laminated Dielectric CTS Element

(U) Figure 8. Inhomogeneous Structures

Additional advantages in millimeter-wave and quasi-optical filter and coupler markets can be realized due to the enhanced producibility and relative low loss of the CTS element over stripline, microstrip, and even waveguide elements. Filter and coupler capabilities can be fully integrated with radiator functions in a common structure.

Performance advantages include:

- Superior aperture efficiency/enhanced filter "Q", approximately one-half the loss of dielectrically-filled waveguide.
- Superior frequency bandwidth of up to one octave per axis, with no resonant components or structures.
- Superior broadband polarization purity, typically -50 dB cross-pol.
- Superior broadband element excitation range and control, coupling values from -3 dB to -35 dB per element are realizable.
- Superior broadband shaped-beam capability. Nonuniform excitation phase is implemented through modulation of stub length and/or position.
- Superior E-plane element factor. Recessed groundplane allows for wide scanning capability, even to endfire.
- Superior power handling capability.

Producibility advantages include:

- Superior insensitivity to dimensional and material variations, <0.50 dB coupling variation for 20 percent change in dielectric constant, no resonant structures.
- Totally externalized construction.
- Simplified fabrication procedures and processes. Units can be thermoformed/extruded/injected in a single molding process, and no additional joining or assembly is required.
- Reduced design NRE costs and cycle time through modular/scalable design, simple and reliable RF theory/analysis, and two-dimensional complexity which is reduced to one dimension.

Application advantages include:

- Very thin profile.
- Lightweight.
- Conformal array can be curved without affecting internal coupling mechanisms.
- Superior durability with no internal cavities.
- Dual-polarization/dual-band/dual beam capable.
- Frequency-scannable.
- Electronically scannable.
- Reduced radar cross section (RCS).
- Applicable at millimeter-wave and quasi-optical frequencies.
- Integrated filter/coupler/radiator functions in common structure.

4.0 CTS Element Variants and Applications

There are several variations on the basic CTS element that may [illegible] useful in particular applications. They are:

4.1 Nondielectrically Loaded

A low density foam can be used as the transmission line medium for the CTS element as shown in Figure 7 to realize an efficient element for an endfire array. The CTS radiator is particularly well-suited in such applications due to its broad pseudo-uniform E-plane element pattern, even at endfire.

4.2 Slow-Wave/Inhomogeneous Structures

Figure 8 shows that an artificial dielectric or multiple dielectric can be used in the parallel plate region in applications for which minimal weight, complex frequency dependence, or precise phase velocity control is required.

4.3 Oblique Incidence

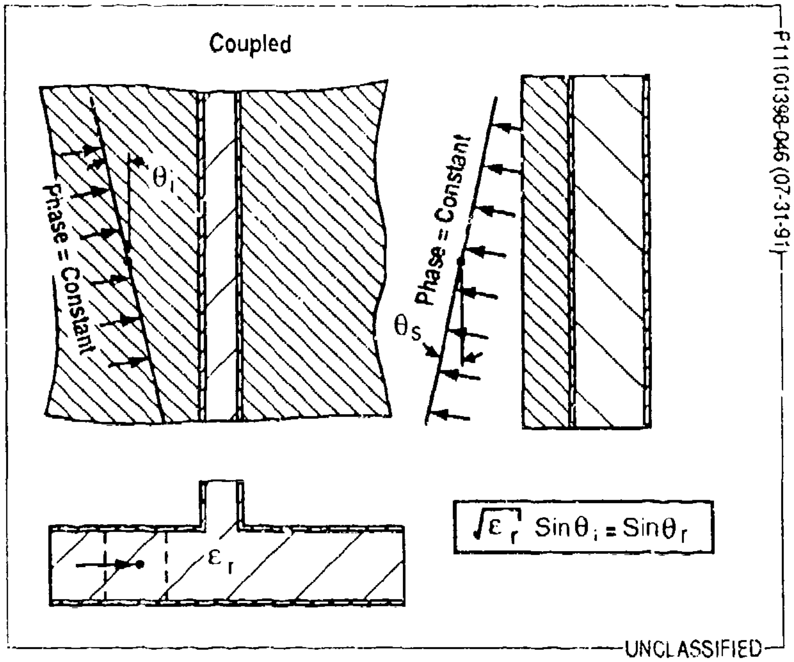
As shown in Figure 9, an oblique incidence of propagating waveguide modes can be achieved through mechanical or electrical variation of the incoming phase front relative to the CTS radiator element axis for scanning the beam in the transverse H-plane. This variation would normally be imposed through mechanical or electrical variation of the primary line feed exciting the parallel plate region. The precise scan angle of this scanned beam will be related to the angle of incidence of the waveguide mode phase front via Snell's Law. That is, refraction will occur at the stub/freespace interface in such a way as to magnify any scan angle imposed by the mechanical or electrical variation of the line feed. This phenomenon can be exploited to allow for relatively large antenna scan angles with only small variations in line feed orientation/phasing. Coupling values can be expected to be pseudo-constant (cosine-dependent) for small angles of incidence.

4.4 Longitudinal Incidence

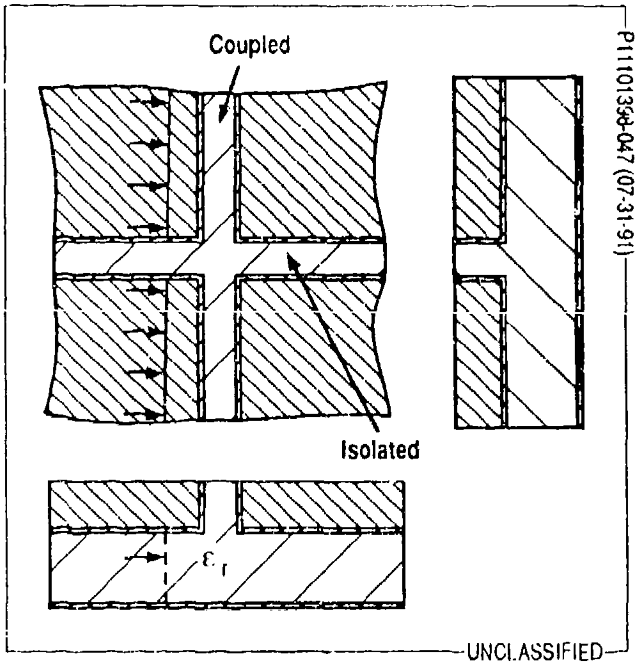
A narrow CTS element will not couple dominant waveguide modes having phase fronts parallel to the stub axis. This characteristic, shown in Figure 10, can be exploited through implementation of orthogonal CTS radiator elements in a common parallel plate region. In this way, two isolated, orthogonally polarized antenna modes can be simultaneously supported in a shared aperture for the purpose of realizing dual-polarization, dual-band, or dual-beam capabilities.

4.5 Parameter Variation in the Transverse Dimension

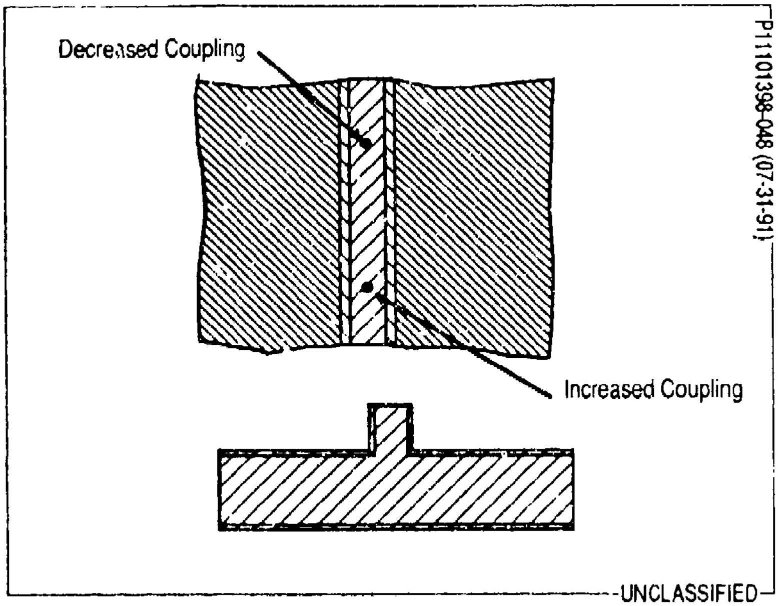
Slow variation of stub dimensions in the transverse dimension can be used to realize tapered coupling in the transverse plane, as shown in Figure 11. This capability proves useful in antenna array applications in which nonseparable aperture distributions are desirable or for nonrectangular array shapes. The modified element is called a quasi-continuous transverse stub (QCTS.) Analysis results based on the continuous transverse slot model can be expected to remain locally valid for the case of transverse variation, assuming that variation profiles are smooth and gradual.



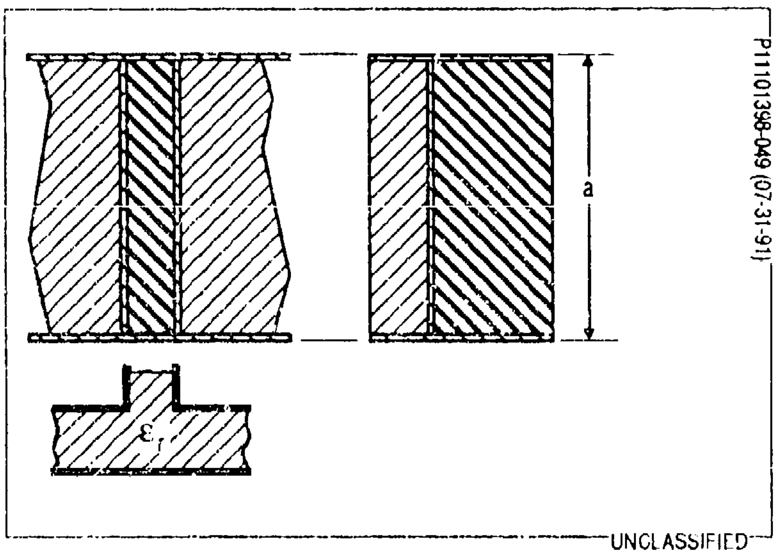
(U) Figure 9. H-Plane Scanning Utilizing a Canted Phase-Front



(U) Figure 10. Dual-Aperture Realization Utilizing CTS Elements



(U) Figure 11. Quasi-Continuous Transverse Stub (QCTS)



(U) Figure 12. Truncated CTS Element

4.6 Finite Width Element

Although conventionally very wide in the transverse extent, the CTS element can be utilized in reduced width configurations down to and including simple rectangular waveguide. The sidewalls of such a truncated CTS element, shown in Figure 12, may be terminated in short circuits, open circuits, or loads as dictated by the particular application.

4.7 Multistage Stub/Transmission Sections

Figure 13 shows that multiple stages can be employed in the stub or parallel plate regions to modify coupling or broaden frequency bandwidth characteristics of the structure as dictated by specific electrical and mechanical constraints.

4.8 Paired Elements (Matched Couplet)

Figure 14 shows how pairs of closely spaced similar CTS radiator elements can be used to customize composite antenna element factors or to minimize composite element VSWR through destructive interference of individual reflection contributions. Bandpass filter implementations can also be realized in a similar fashion when purely reactive CTS elements are used.

4.9 Radiating/Nonradiating Stub Pairs (Matched Couplet)

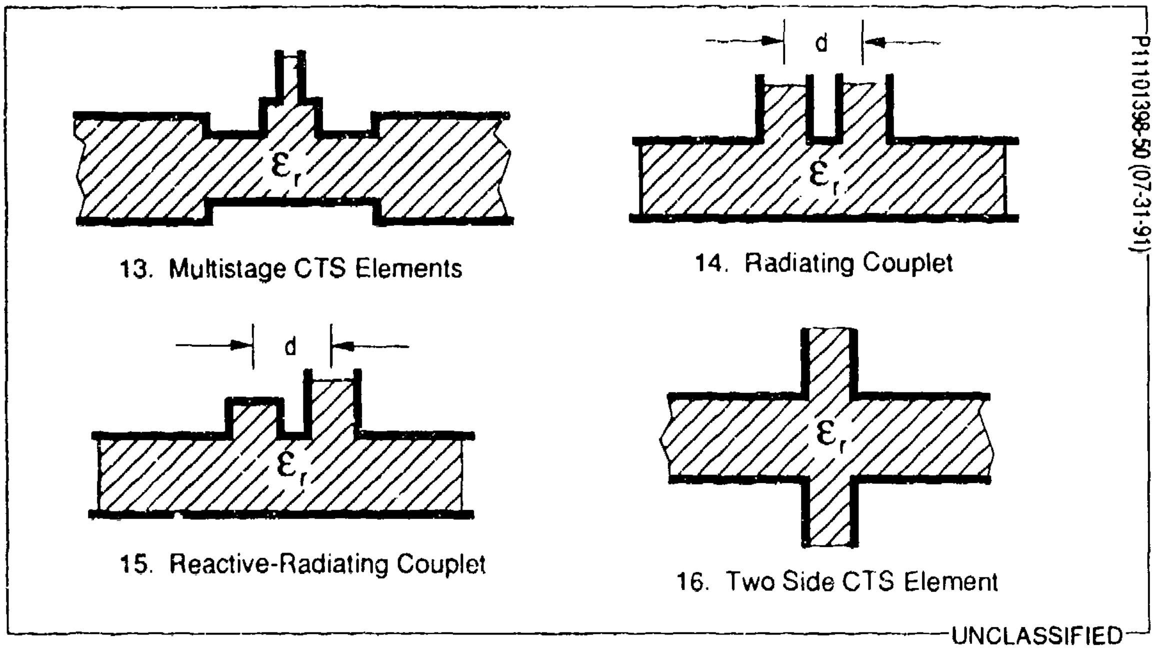
Figure 15 shows how a nonradiating purely reactive CTS element can be paired with a CTS radiator element to suppress coupler/radiator reflections through destructive interference of individual reflection contributions, resulting in a matched CTS couplet element. Such couplet elements may prove particularly useful in CTS array antennas when scanning the beam at or through broadside is required.

4.10 Double Sided Radiator/Filter

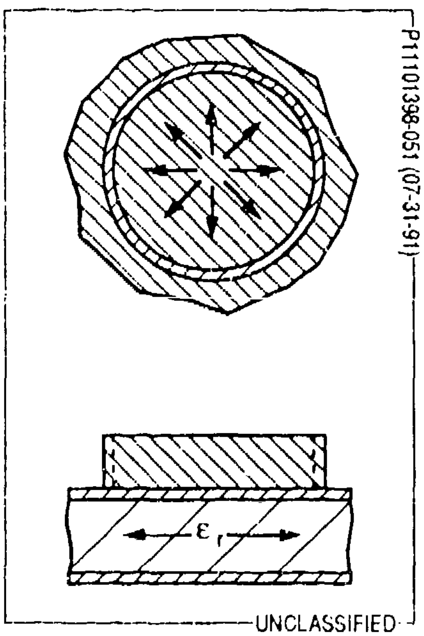
Figure 16 shows how radiator, coupler, and/or reactive stubs can be realized on both sides of the parallel plate structure to economize space or for antenna applications in which radiation from both sides of the parallel plate is desirable.

4.11 Radial Applications

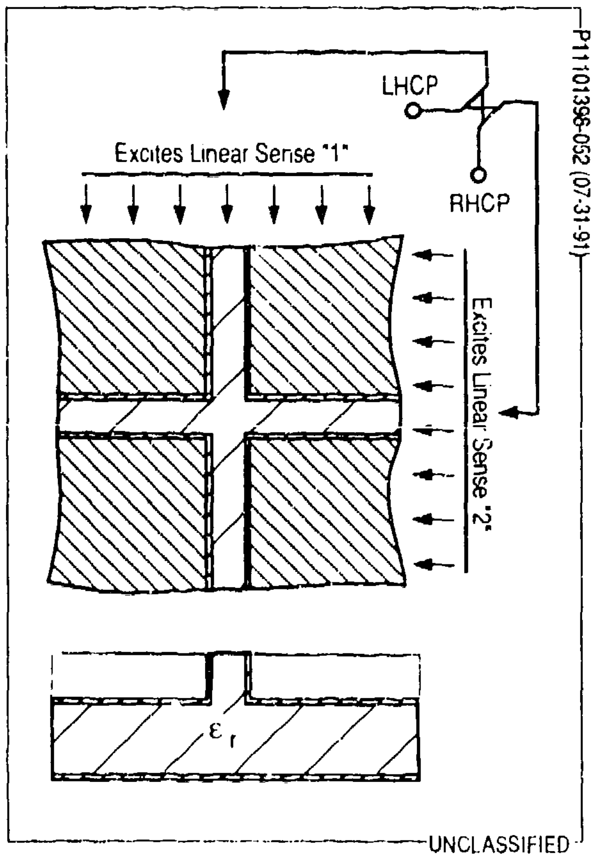
The CTS element can be utilized in applications in which cylindrical waveguide modes are used in place of plane waveguide modes. As shown in Figure 17, the CTS element forms closed concentric rings in this



(U) Figure 13-16. Multistage Stub/Transmission Sections



(U) Figure 17. Annular Ring CTS Element



(U) Figure 18. Circular Polarization Utilizing CTS Elements radial configuration with coupling mechanisms and characteristics similar to those for the plane wave case. Single or multiple point sources serve as a primary feed. Both radiating and nonradiating versions of the CTS element can be realized for the cylindrical case. Such arrays may be particularly useful for antennas requiring high gain 360 degree coverage oriented along the radial direction and in one-port filter applications.

4.12 Circular Polarization

Although the CTS radiator element is exclusively a linearly polarized antenna element, Figure 18 shows how circular polarization can be realized in a straightforward fashion either through a standard quarter-wave plate polarizer or through quadrature coupling of orthogonally oriented CTS radiator elements or arrays.

5.0 Array Variants and Applications

The CTS element can be combined or arrayed to form a planar structure fed by an arbitrary line source. This line source may be either a discrete linear array, such as a slotted waveguide, or a continuous linear source, such as a pill-box or sectoral horn. Two line sources are used in filter and coupler applications to form a two-port device. In the case of antenna applications, a single line feed is utilized to impose the desired aperture distribution in the transverse plane while the parameters of individual CTS radiator elements are varied to control the aperture distribution in the longitudinal plane.

In filter and coupler applications, a second line feed can be introduced to form a two-port device comprised of CTS coupler or reactive elements. For antenna applications, either a short circuit, open circuit, or load can be placed at end of the CTS array opposite the line source to form a conventional standing wave or traveling wave feed.

Standard array, coupler, and filter synthesis and analysis techniques can be used in the selection of interelement spacings and electrical parameters for individual CTS elements in CTS array specifications. Normalized design curves relating the physical attributes of the CTS element to electrical parameters are derived either analytically or empirically to realize the desired CTS array characteristics.

The simple modular design of the CTS array greatly reduces the design NRE costs and cycle time associated with conventional planar arrays. Typical planar array developments require the individual specification and fabrication of each discrete radiating element along with associated feed components such as angle slots, input slots, and corporate feed. In contrast, the CTS planar array requires the specification of only two linear feeds, one comprised of the array of CTS elements, the other of the requisite line feed. These feeds can be designed and modified separately and concurrently and are fully specified by a minimum number of unique parameters. Drawing counts and drawing complexities are thus reduced. Design modifications or iterations are easily and quickly implemented.

5.1 Pencil Beam Array

A standard pencil beam antenna array as shown in Figure 19 can be constructed using the CTS array concept with principle plane excitations implemented through appropriate selection of line source and CTS element parameters. Element spacings are conventionally chosen to be approximately equal to an integral number of wavelengths within the parallel plate region. Monopulse functions can be realized through appropriate modularization and feeding of the CTS array aperture

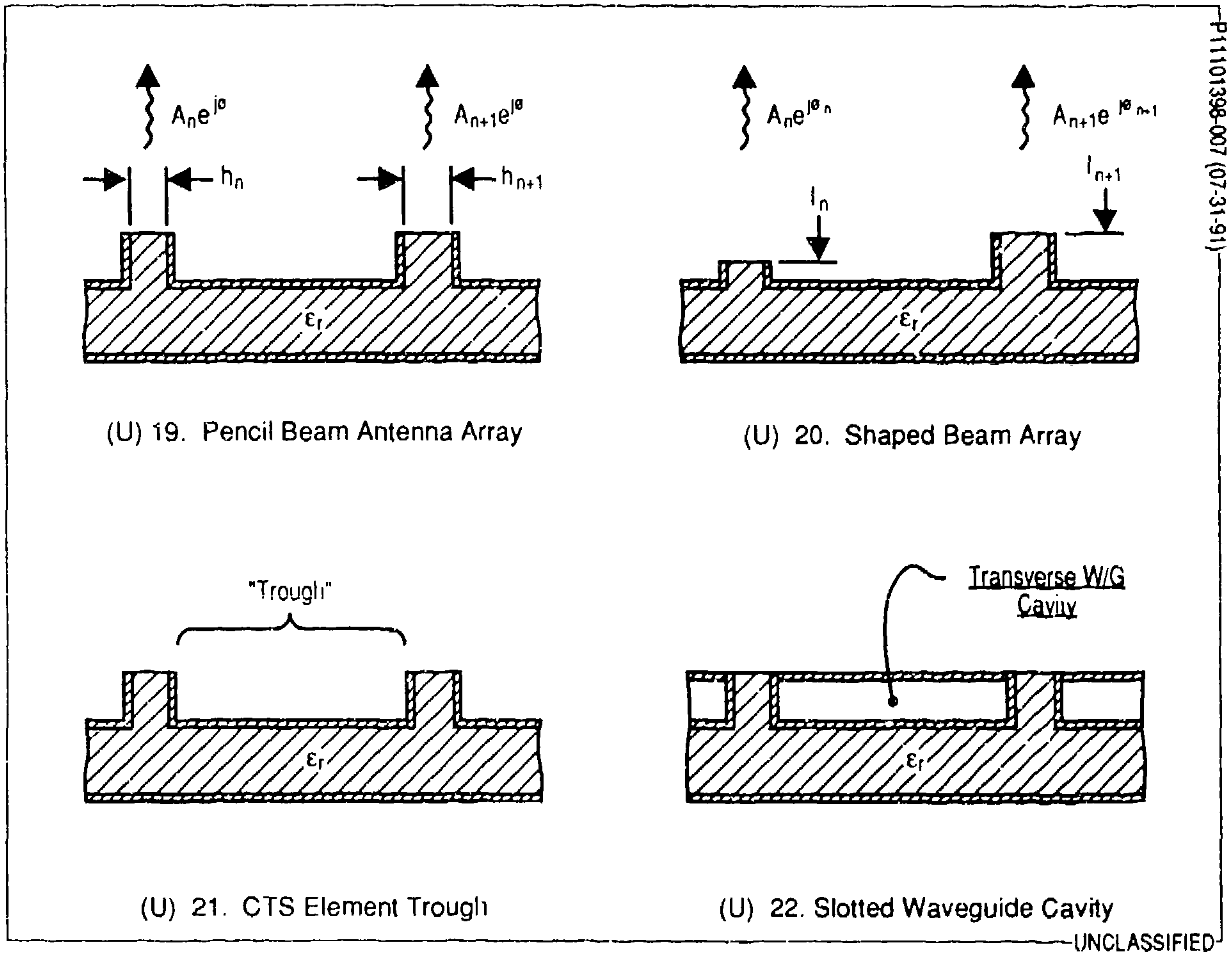
5.2 Shaped Beam Array

The variable length of the stub portion of the CTS radiator allows for convenient and precise control of individual element phases in CTS antenna array applications. This control, in conjunction with the CTS element's conventional capability for discrete amplitude variation, allows for precise specification and realization of complex shaped beam antenna patterns, as shown in Figure 20. Examples include cosecant-squared and nonsymmetric sidelobe applications.

5.3 Multi-Aperture Array

The continuous stubs of a CTS array typically occupy no more than 10 to 20 percent of the total planar antenna aperture or filter area. The radiating apertures of these stubs are at their termination and are therefore raised above the groundplane formed by the main parallel plate transmission line structure. Relatively wide, continuous, transverse, conductive troughs are therefore formed between individual CTS elements as shown in Figure 21. These troughs can be exploited to introduce secondary array structures.

Possible exploitations include closing the trough to form a slotted waveguide cavity as shown in Figure 22; interdigitation of a printed patch array; slotting of the trough region to couple alternative modes from the parallel plate transmission line; or introduction of active elements as adjuncts to the CTS array structure.



(U) Figure 19-22. CTS Array Applications

5.4 Dual Polarization Array

An identical pair of orthogonally oriented CTS arrays can be utilized as shown in Figure 23 to realize a dual-polarization planar array sharing a common aperture area. Circular or elliptical polarizations can be realized through appropriate combination of the two orthogonal signals via a fixed or variable quadrature coupler or with the introduction of a conventional linear-to-circular polarizer. The pure linear polarization of individual CTS radiating elements and the natural orthogonality of the parallel plate waveguide modes provides this approach with superior broadband polarization isolation.

5.5 Dual-Beam Array

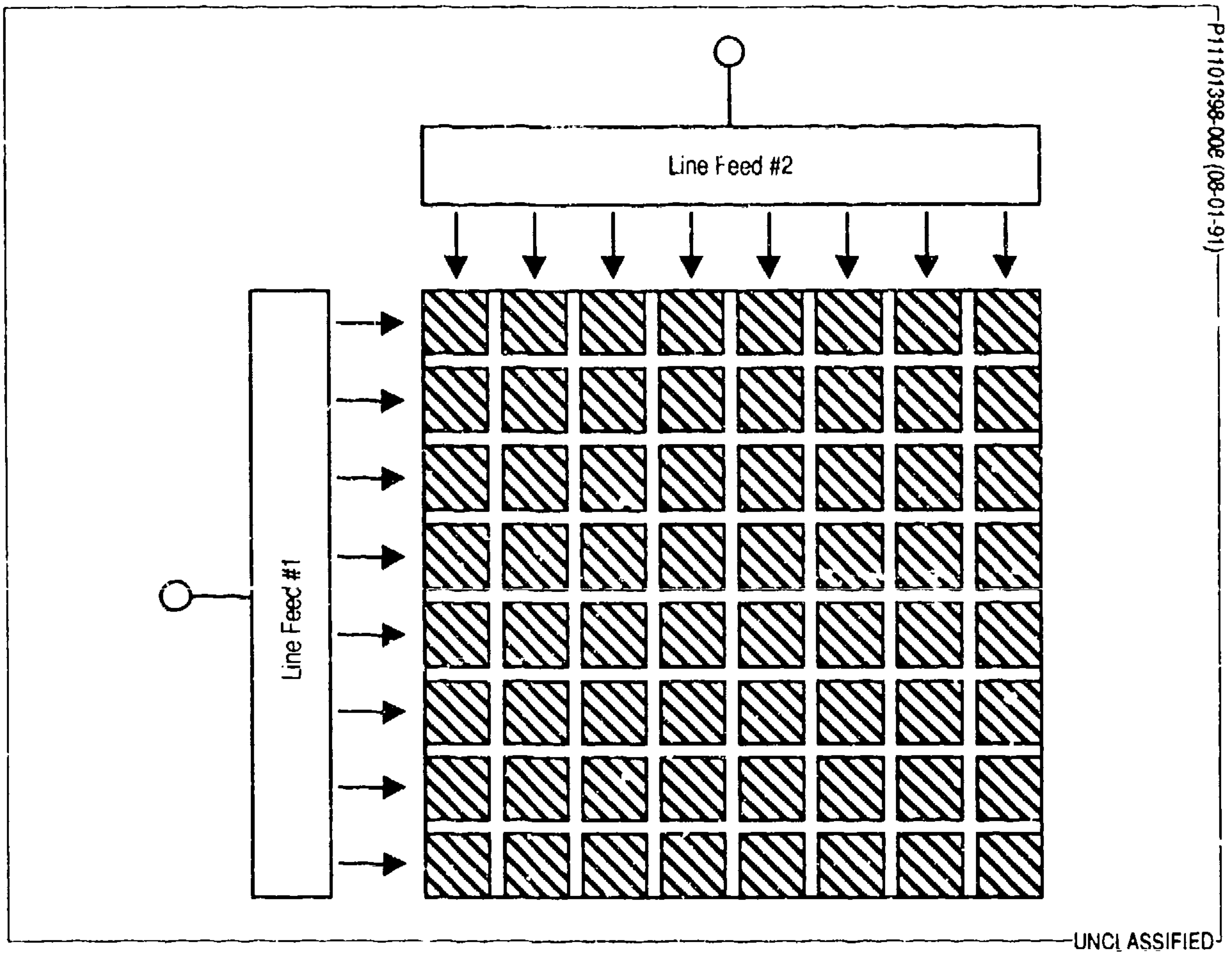
In a manner similar to the dual polarization approach, two dissimilar orthogonally oriented CTS arrays can be employed to provide a simultaneous dual antenna beam capability. For example, one CTS array might provide a vertically polarized pencil beam for air-to-air radar modes while another provides a horizontally polarized cosecant-squared beam for ground mapping. Dual squinted pencil beams for microwave relay represents a second application of this dual beam capability.

5.6 Dual-Band Array

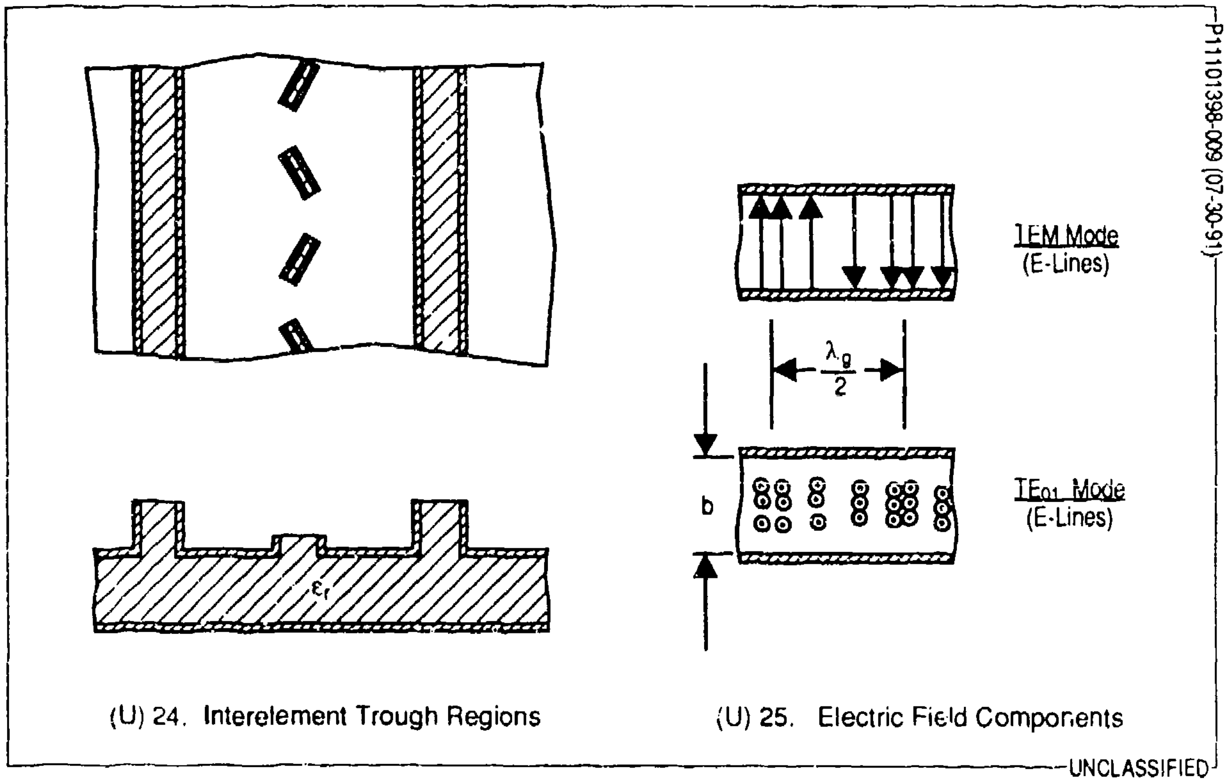
Again utilizing a pair of orthogonally oriented CTS arrays, a dual-band planar array can be constructed through appropriate selection of interelement spacings and CTS element parameters for each array. The two selected frequency bands can be widely separated due to the dispersionless nature of the parallel plate transmission line structure and the frequency independent orthogonality of the waveguide modes.

5.7 Dual Guided Mode Array

Periodically spaced slots can be introduced in the trough regions between individual CTS array elements to couple alternative mode sets from the parallel plate transmission line structure. For example, a TE mode whose electric field vector is oriented parallel to the conducting plates of the parallel plate transmission line may be selectively coupled through the introduction of thick or thin inclined slots in the interelement trough regions, as shown in Figure 24. These slots may protrude slightly from the conductive plate groundplane to aid in fabrication. Such a mode is not coupled by the CTS elements due to the transverse orientation of its induced wall currents and the cut-off conditions of the CTS stubs. Likewise, the waveguide modes of the parallel plate waveguide structure, with its electric field vector oriented perpendicular to the conducting plates of the parallel plate transmission line, are not coupled to the inclined slots due to the disparity in operating and slot resonant frequencies, particularly for thick slots. In this way a dual-band planar array is formed with frequency band offsets regulated by the



(U) Figure 23. Dual Polarization Array



(U) 24. Interelement Trough Regions

(U) 25. Electric Field Components

(U) Figure 24-25. Multimode Capabilities interelement spacing of the CTS and inclined slot elements and the parallel plate spacing of the parallel plate transmission line.

Figure 25 shows the electric field components for TEM and TE_{01} modes. Dual-beam and dual-polarization apertures may also be realized using intentional multimode operation.

5.8 Fixed or Variable H-Plane Beam-Squint Array

As shown in Figure 26, an intentional fixed or variable beam squint (in one or both planes) can be realized with a CTS array through appropriate selection of CTS array element spacing, constituent material dielectric constant, or requisite line feed characteristics. Such a squinted array may be desirable for applications in which mounting constraints require deviation between the mechanical and electrical boresights of the antenna.

5.9 H-Plane Scanning by Mechanical Dithering of Line-Feed

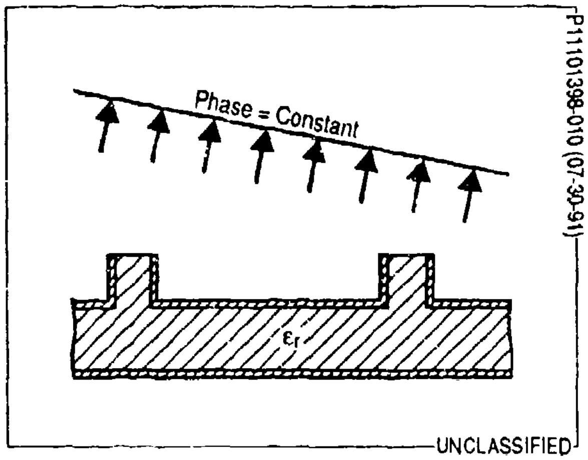
The requisite line feed for a CTS antenna array can be mechanically dithered to vary the angle of incidence, or phase slope, of the propagating parallel plate waveguide modes relative to the CTS element axis. In doing so, a refraction enhanced beam squint of the antenna beam is realized in the transverse H-plane of the array, as shown in Figure 27.

5.10 H-Plane Scanning by Electrical Variation of Line-Feed Propagation Constant

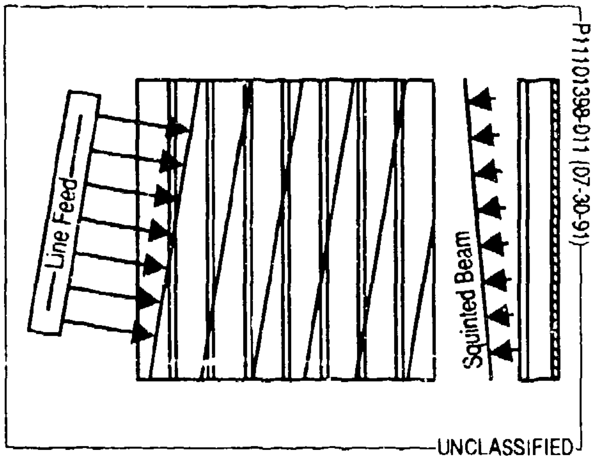
Figure 28 shows an alternate method of varying of the angle of incidence of the propagating parallel plate waveguide modes relative to the CTS element axis. Such variation causes squinting of the phase front emanating from the line source while maintaining a fixed, parallel, mechanical orientation relative to the CTS element axis.

5.11 E-Plane Scanning by Variation of Planar Propagation Constant

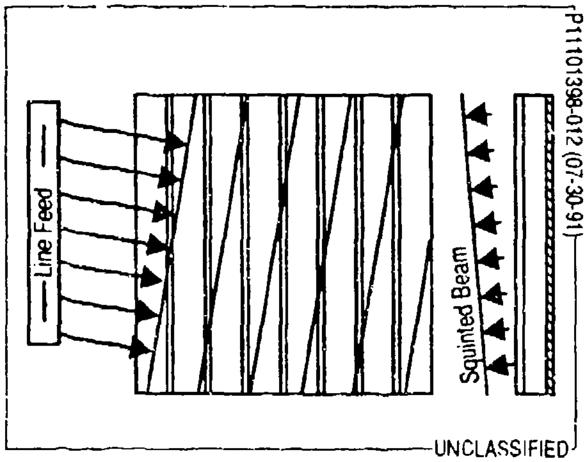
Variation of the phase velocity within the parallel plate transmission line structure will scan the beam in the longitudinal E-plane. Such a variation may be induced through appropriate electrical or mechanical modulation of the constituent properties of the dielectric material contained within the parallel plate region. This scanning technique can be combined with scanning techniques in the transverse plane to achieve simultaneous beam scanning in two dimensions. This is the basic Hughes approach for exploiting voltage-controlled dielectric materials.



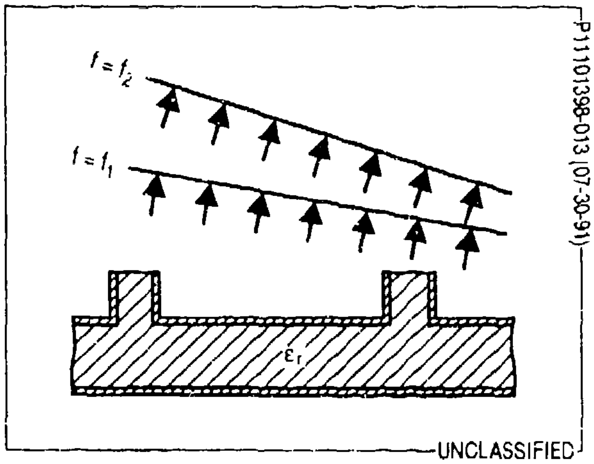
(U) Figure 26. Squint Beam Array



(U) Figure 27. Mechanical Line Feed Scanning



(U) Figure 28. Line Feed Phase Velocity Variation Scanning



(U) Figure 29. Frequency Scanning

This modulation in phase velocity within the parallel plate transmission line structure can also be used in CTS array filter and coupler structures to frequency tune their respective passbands or stopband responses.

5.12 E-Plane Frequency Scanning

As shown in Figure 29, when used as a traveling wave antenna array structure, the position of the antenna mainbeam will vary with frequency. In applications where this phenomenon is desirable, interelement spacings and material dielectric constant values can be chosen to enhance this frequency dependent effect. For example, a CTS array fabricated from a high dielectric material (e_r=12) will exhibit approximately a two degree beam scan for a one percent variation in operating frequency.

5.13 Conformal Array

The absence of internal details within the CTS structure allows for convenient deformation of its shape to conform to curved mounting surfaces, e.g., wing leading edges, missile/aircraft fuselages and automobile bodywork. As shown in Figure 30, the overmoded nature of the CTS structure allows such deformation to large radii of curvature without perturbation of its planar coupling characteristics.

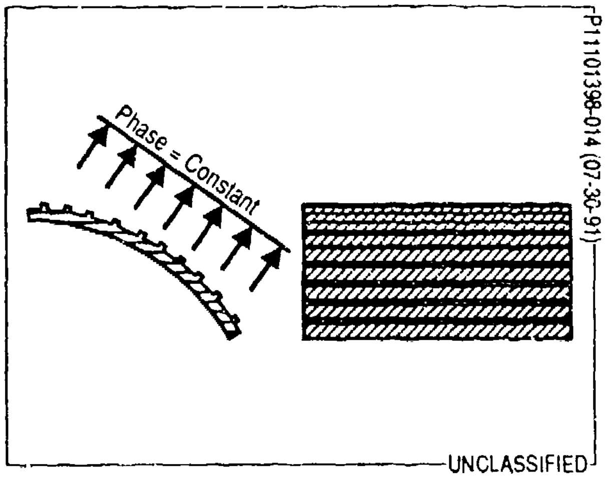
The interelement trough regions in the CTS array structure can provide a means for suppression of undesirable surface wave phenomena normally associated with conformal arrays. Deformation of the radiated phase front emanating from such a curved CTS array may be corrected to planar through appropriate selection of line feed and individual CTS element radiator phase values.

5.14 End-fire Array

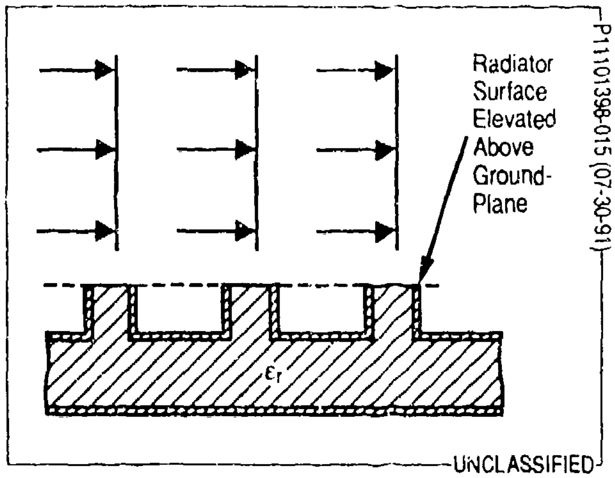
The CTS array can be optimized for endfire operation, as shown in Figure 31, through appropriate selection of interelement spacings and constituent material characteristics. The elevated location relative to the interstub groundplane of the individual CTS radiator element surfaces affords a broad element factor and yields a distinct advantage to the CTS element in endfire applications.

5.15 Non-Rectangular Apertures

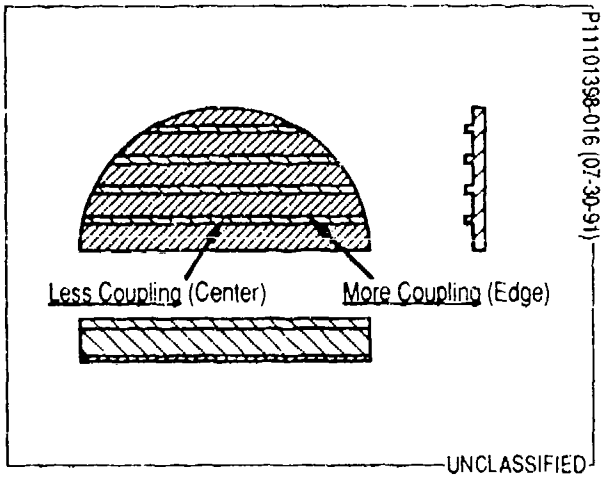
As shown in Figure 32, variation of CTS element parameters in the transverse plane yields a quasi-continuous transverse stub (QCTS) element that can be used in QCTS arrays for which nonseparable aperture distributions or nonrectangular aperture shapes (circular or elliptical) are desired. For continuous, smoothly varying modulation of QCTS element parameters, the excitation, propagation, and



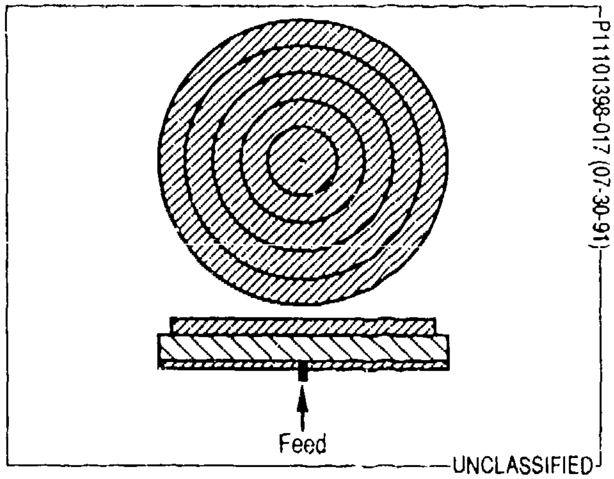
(U) Figure 30. Conformal Array



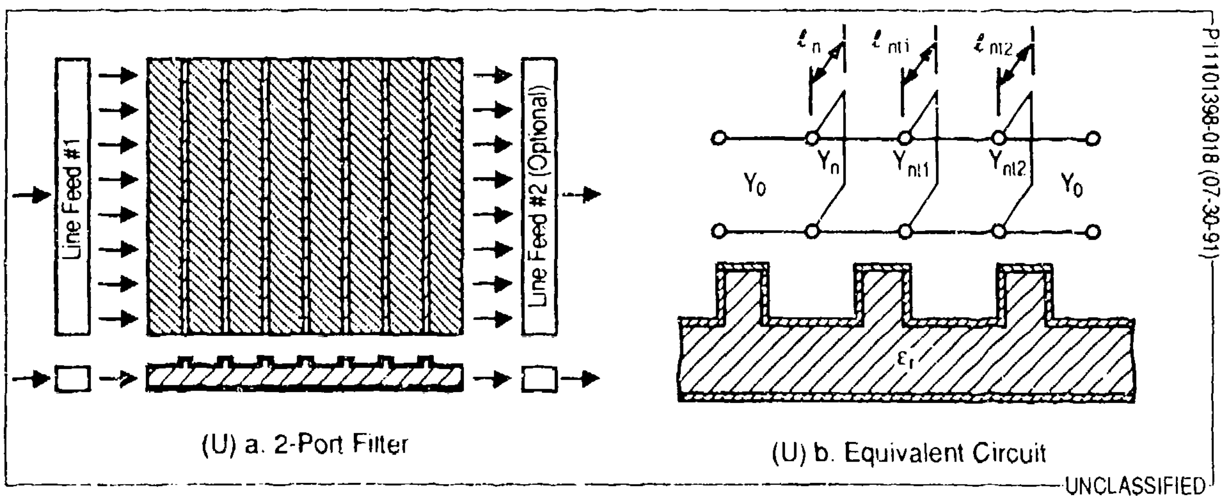
(U) Figure 31. Endfire Array



(U) Figure 32. Nonseparable Shaped Array



(U) Figure 33. Radial Array



(U) a. 2-Port Filter

(U) b. Equivalent Circuit

(U) Figure 34. CTS Filters

coupling of higher order modes within the QCTS array structure can be assumed to be locally similar to that of the standard CTS array and hence the CTS array design equations can be applied locally across the transverse plane in QCTS applications.

5.16 RCS Characteristics

The absence of variation in the transverse plane for CTS arrays eliminates scattering contributions (Bragg lobes) which would otherwise be present in traditional two-dimensional arrays comprised of discrete radiating elements. In addition, the dielectric loading in the CTS array allows for tighter interelement spacing in the longitudinal plane and therefore provides a means for suppression or manipulation of Bragg lobes in this plane. The capability to intentionally squint the mainbeam in CTS array applications also affords it an additional design advantage in RCS performance.

5.17 Radial CTS Arrays

As shown in Figure 33, the CTS array can also be realized in radial form, in which case the continuous transverse stubs form continuous concentric rings. A single or a multimode point source replaces the traditional line source in such applications. Radial waveguide modes are used in a similar manner to plane waveguide modes to derive design equations for the radial CTS array.

Dual-polarization, dual-band, and dual-beam capabilities can be realized with the radial CTS array through appropriate selection of feeds, CTS element, and auxiliary element characteristics in a manner directly parallel to that for the planar CTS array. Similar performance, application, and producibility advantages apply. Both endfire and broadside mainbeam patterns can be realized with the radial CTS array.

5.18 Filters

As shown in Figure 34, nonradiating reactive CTS elements terminated in an open or short circuit can be arrayed to conveniently form filter structures. Such structures can function independently as filters or be combined with radiating elements to form an integrated filter/multiplexer/antenna structure. Conventional methods of filter analysis and synthesis may be employed with the CTS array filter without loss of generality.

The CTS array enjoys advantages over conventional filter realizations, particularly at millimeter-wave and quasi-optical frequencies where its diminished dissipative losses and reduced mechanical tolerance sensitivities allow for the efficient fabrication of high precision, high "Q" devices. Note that the theoretical dissipative losses for the CTS array parallel plate transmission line structure are approximately one-half of those associated with a standard rectangular waveguide operating at the identical frequency and comprised of identical dielectric and conductive materials.

5.19 Couplers

As well as for filters as shown in Figure 35, precision couplers may also be realized and integrated using the CTS array structure with individual CTS elements functioning as branch guide surrogates. Again, conventional methods of coupler analysis and synthesis can be used without loss of generality.

6.0 Fabrication Methods

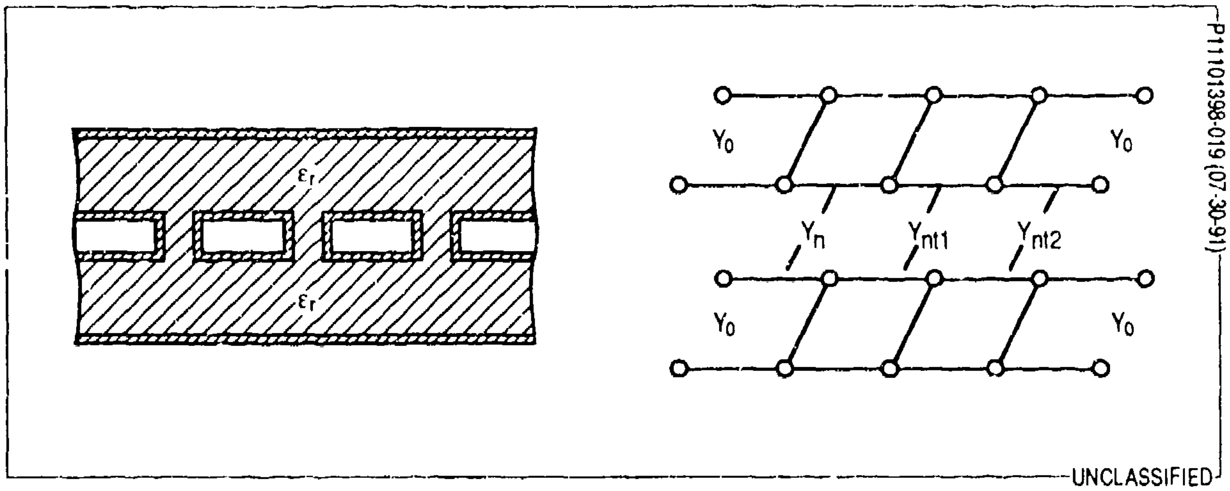
Fabrication of the dielectrically loaded CTS element can be efficiently accomplished through machining or molding of the dielectric structure, followed by uniform conductive plating to form the parallel plate transmission line, and finally, in the case of antenna applications, machining or grinding of the stub terminus to expose the stub radiator.

Mature fabrication technologies such as extrusion, injection molding, and thermomolding are ideally suited to the fabrication of CTS arrays. In many cases the entire CTS array, including all feed details, can be formed in a single exterior molding operation.

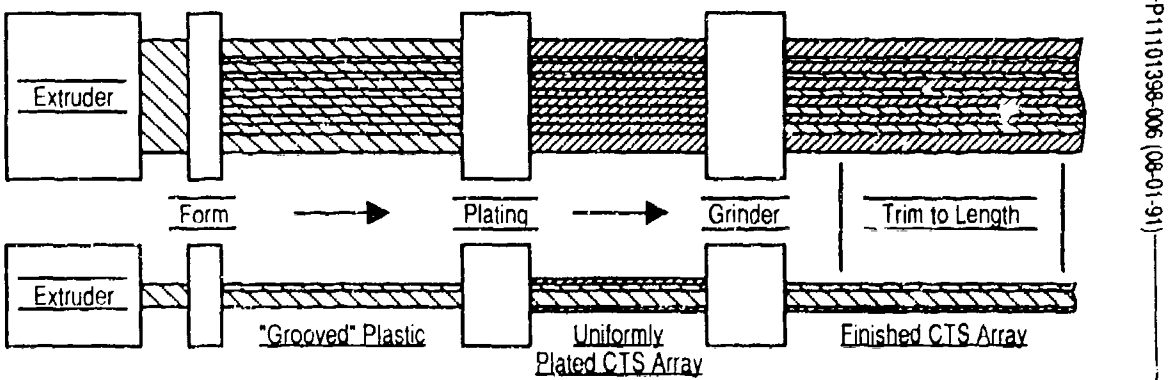
A typical three step fabrication cycle includes structure formation by continuous extrusion or closed single step molding; uniform exterior metalization by plating, painting, lamination, or deposition; and planar grinding to expose input, output, and radiating surfaces. Due to the absence of interior details, the CTS array requires metalization on exterior surfaces only with no stringent requirement for metalization thickness, uniformity, or masking.

Figure 36 shows a typical continuous extrusion process whereby the stubs of the CTS array structure are formed, metalized, and trimmed in a continuous sequential operation. Such an operation results in long CTS array sheets which may subsequently be diced to form individual CTS array structures. Figure 37 depicts a similar discrete process by which individual CTS array structures are molded or formed, metalized, and trimmed in a sequence of discrete operations.

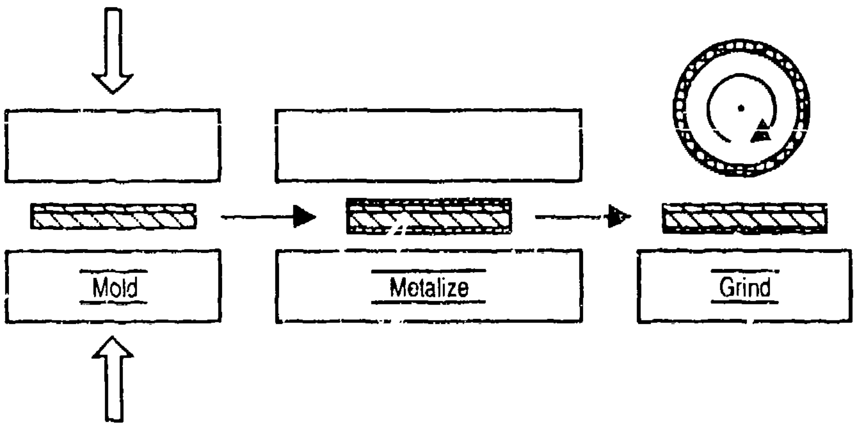
The relative insensitivity of the nonresonant CTS element to dimensional and material variations greatly enhances its producibility over competing resonant approaches. This, in conjunction with the relative simplicity of the design and fabrication of the CTS array, makes it an ideal candidate for low cost high production rate applications.



(U) Figure 35. CTS Couplers



36. Extrusion Fabrication Example



37. Pressing Fabrication Example

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(U) Figure 36-37. CTS Fabrication Options

7.0 Specific Application Examples

As an initial effort, a small CTS antenna array was fabricated to demonstrate the CTS element and array concepts for antenna applications. Coarse approximations for coupling and radiating characteristics were used in lieu of precise analytical models and empirical design data. This test piece was thus a feasibility demonstration and not an optimized design.

A 6.0 by 10.5-inch CTS antenna array was fabricated from rexolite (e_r=2.35, ltan=0.0003). This array was comprised of 20 CTS radiator elements and designed for operation in the 12.5 to 18 GHz frequency band. A moderate amplitude excitation taper was imposed in the longitudinal plane through appropriate variation of CTS stub widths having constant individual heights. Interelement spacing was 0.500 inch and parallel plate spacing was 0.150 inch. A silver based paint provided a uniform conductive coating over all exposed areas of the CTS array. Input and stub radiator surfaces were exposed after plating using a mild abrasive.

An H-plane sectoral horn, 0.15 by 6 inches, was designed and fabricated as a simple low cost Ku-band line source, providing a cosinusoidal amplitude and a 90 degree peak-to-peak parabolic phase distribution at the input of the CTS array. A quarter-wave transformer was built into the CTS array to match the interface between it and the sectoral horn line source.

E-plane antenna patterns were measured for the CTS antenna array over the frequency band of 13 to 17.5 GHz, exhibiting a well-formed mainbeam with <-13.5 dB sidelobe level over the entire frequency range. Cross polarization levels were measured and found to be better than -50 dB. H-plane antenna patterns exhibited characteristics identical to that of the sectoral horn itself, consistent with the separable nature of the aperture distribution used for this configuration. Figure 38 shows a measured E-plane pattern for this CTS array measured at 17.5 GHz.

A second design, fabrication, and test of a planar CTS array was performed at 60 GHz. A 6 by 6 inch aperture was fabricated from rexolite, copper-sputtered, and measured. A folded half-pillbox antenna was used as a line source. Figure 39 shows the completed array. Figure 40 shows the measured E-plane pattern for the array, demonstrating a 1.75 degrees beamwidth. An aperture efficiency of 71 percent was measured, compared with approximately 10 percent for printed antennas of similar size and gain.

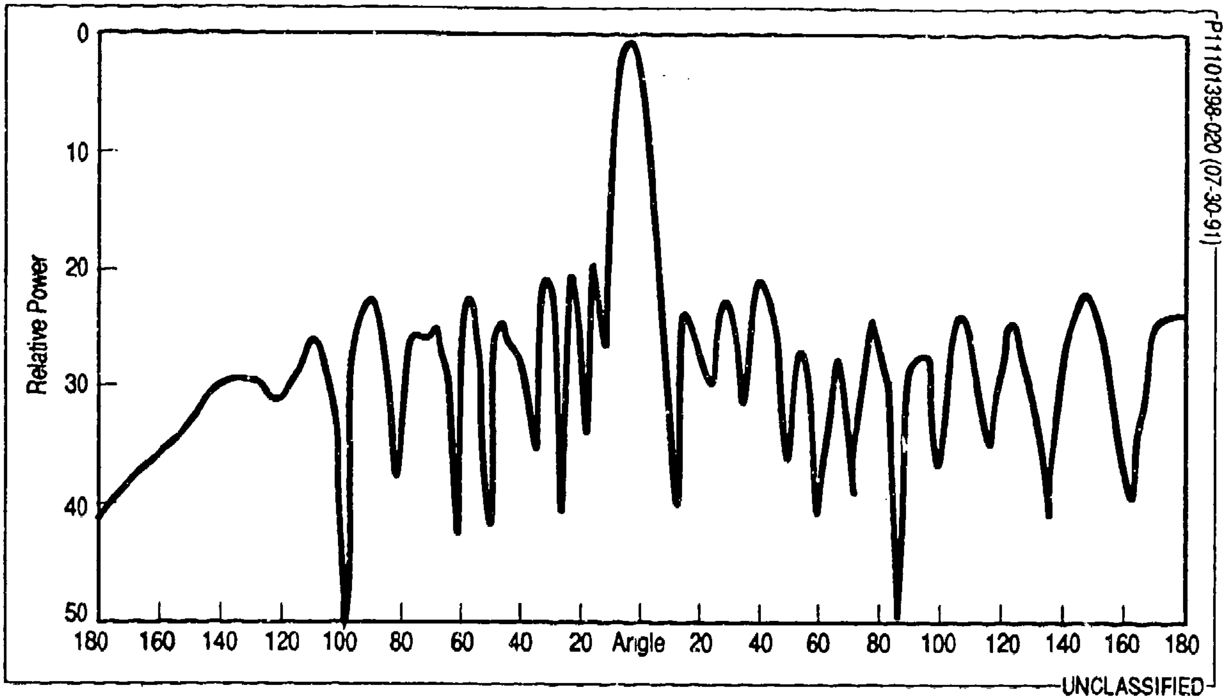
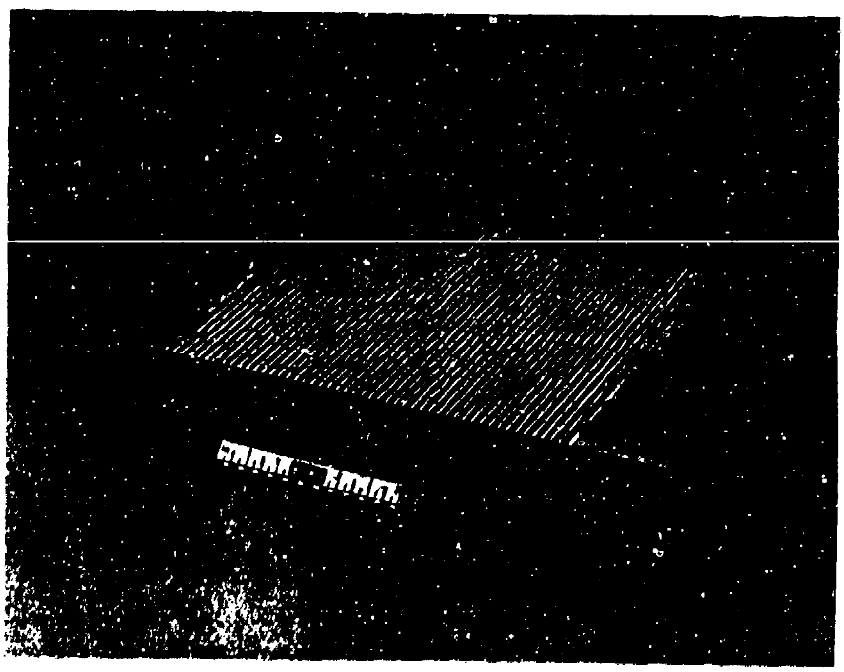
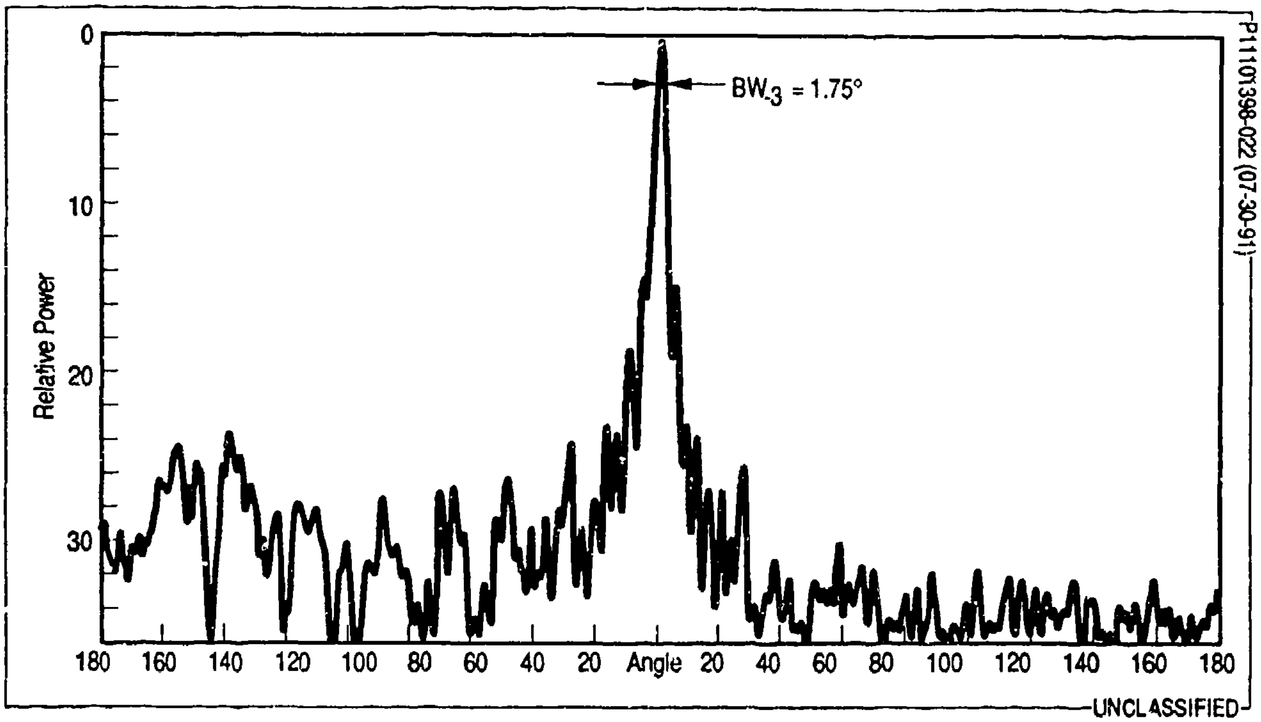


Figure 38. Measured Performance of Breadboard CTS Array at 17.5 GHz



(U) Figure 39. Array Used in Second Test Series



(U) Figure 40. Measured Performance of Millimeter-Wave CTS Array at 60 GHz

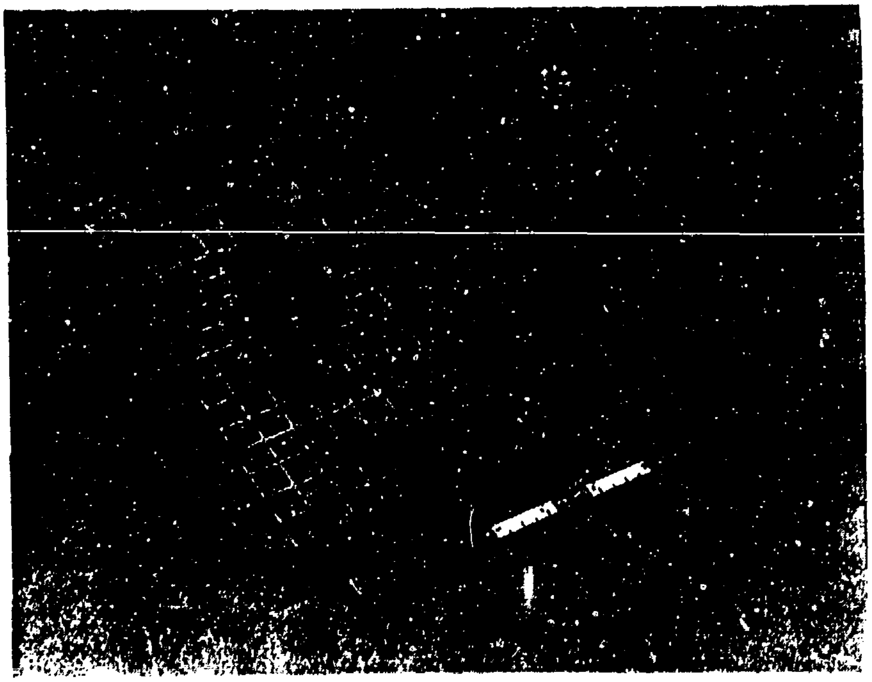


Figure 41. Dual-Polarization CTS Array (Ku-Band)

8.0 Continuing and Future Development

Current ongoing developments of the CTS antenna array include fixed and one-dimensional scanning applications at 12, 33-50, 35, and 94 GHz. These applications include both single and dual polarization realizations for the military, automotive, commerical avionics, and consumer marketplaces. As an example, Figure 41 depicts a prototype dual-polarization Ku-band CTS array currently under development as a low-cost planar antenna for the Direct Broadcast Satellite (DBS) consumer market. Applications of dual-band, two-dimensional scanning, and conformal capabilities have been formally proposed.

Analytical developments underway include improved equivalent circuit, mode-matching and finite-element models in order to more rigorously account for mutual-coupling, fringing, and dissipative loss effects. Analysis of inhomogeneous, time-varying, and anisotropic dielectric materials and CTS geometries have been proposed.