INTEGRATED TAPERED SLOT ANTENNA ARRAYS AND DEVICES

K. Sigfrid Yngvesson

Department of Electrical and Computer Engineering
University of Massachusetts
Amherst, MA 01003

ABSTRACT

The potential advantages of integrating antenna elements/arrays with active devices has made this into an area which has received increasing emphasis among millimeter wave/submillimeter wave researchers. This paper reviews the status of one type of antenna element which shows great promise for such applications - the Tapered Slot Antenna (TSA). We will cover some recent advances in this area, with particular emphasis on the potential application of TSA arrays in THz Space Technology. Examples are given of applications with relevance to THz Space Technology in three areas: (1) Focal plane arrays for imaging; millimeter wave prototypes at 35 and 94 GHz have demonstrated system aperture efficiencies (i.e. total coupling efficiencies) of over 50%, with angular resolution close to the Rayleigh criterion. (2) Quasi-optical power-combining with high radiative efficiency, as demonstrated by a 32 GHz prototype developed together with JPL. (3) Integrated receivers, such as SIS mixers, and a new two-dimensional electron gas element.

REVIEW OF TSA ELEMENTS AND ARRAYS

Endfire antenna elements of the tapered slot antenna (TSA) type can be employed both as single elements and in arrays. TSAs utilize a tapered slot in the metalization on a thin dielectric substrate, to radiate in the "end-fire" direction (along the tapered slot, see Figure 1). The special case of air dielectric also has been investigated. Some distinctive advantages of the TSA elements are (1) the 3 dB beamwidth can be varied over a wide range, down to about 15 degrees (2) ease of fabrication by photoetching, and integration with active elements (3) high packing density when used in arrays (4) high efficiency in phased arrays even with element spacings greater than 1 λ.

Integrated millimeter wave TSA elements were pioneered by Gibson [1] who demonstrated a bandwidth of 8–40 GHz for an exponentially tapered ("Vivaldi") single element, matched to a detector. Since that time, theoretical work by Schaubert and co-workers [2, 3] as well as Johansson [4] has provided a fairly complete picture of the process by which single element TSAs radiate. While TSA elements have many features in common with the general class of traveling-wave antennas, there are some differences: for example, the H-plane beamwidth often follows the $(1/L^{1/2})$ dependence expected for traveling-wave antennas (L = antenna length), while the E-plane beamwidth also depends on the aperture size, and varies more slowly with L [2, 3, 5]. A complete moment-method solution has been presented for the air-dielectric case, and a simplified linearly tapered geometry [4]. Radiation patterns (both co-polarized and cross-polarized) are predicted correctly. An unsolved case is the single element on a dielectric, with a finite substrate width.

As indicated by both theoretical and experimental studies, TSA patterns can have high cross-polarization levels in the diagonal (D) plane. The lowest X-pol levels (10–15 dB below the Co-Pol peak) are obtained for exponentially tapered elements, with an optimum dielectric thickness. For these elements, the integrated power lost to X-Pol, is about 10%. Phase centers have also been predicted and measured in recent work — typically, the E-plane phase center is somewhat behind the aperture, while the H-plane one is further toward the feed-point. A Vivaldi element has been used in one experiment as the feed for an f/D = 1 paraboloid reflector. The dependence of the gain on the axial displacement indicated that for this element E- and H-plane phase centers were close. The aperture efficiency of this system was estimated to be ~55% by direct substitution with a waveguide horn. TSA elements used as feeds for reflectors or lenses, thus yield comparable system aperture efficiency to typical waveguide feeds.

Arrays of TSA elements (Figure 2 shows an example) have a number of useful advantages. They have been employed in the focal plane of a reflector, in order to form a multi-beam system for millimeter wave imaging. One such system demonstrated resolution of two point sources at the Rayleigh distance [6]. When compared at the same beamwidth (to illuminate a specific reflector optimally), elements in a TSA array occupy about 1/4 of the area of a typical waveguide feed element. Thus, imaging systems with TSA focal plane arrays (Figure 3) can be designed to yield high angular resolution (due to small element spacing) while retaining high aperture efficiency. In other multi-beam systems, TSA arrays could be used if a high cross-over level is desired.

Most of the work on TSA elements and arrays thus far has utilized substrates such as low-ε_r Duroid, or Kapton (ε_r = 3.5), and has been limited to 35 or 94 GHz. Recent work has emphasized techniques for enabling TSA arrays to be used at THz frequencies. Kollberg et al are developing a 16 element TSA array for 100 GHz, with integrated SIS mixers, to be used as a focal plane array in a 20 meter diameter radio telescope. The Chalmers University group is also developing TSA elements to be integrated with SIS mixers at 300 GHz [5]. The substrates used are quartz and silicon. The University of Massachusetts group is developing TSAs on GaAs and silicon, to be integrated with Two-dimensional electron gas elements to be described below. The most important constraint is that there is an optimum substrate thickness, which decreases as the dielectric constant goes up. As a rule of thumb, one can use the following relationship:

$$\frac{t_{eff}}{\lambda_0} = .03 - .04 \tag{1}$$

where,

$$t_{eff} = t \times (\varepsilon_r - 1) \tag{2}$$

The optimum thickness (t) of a silicon substrate (with $\varepsilon_r = 11.8$) for a 100 GHz TSA is about 5-10 micrometers. One approach for achieving the required thickness of the substrate is to etch semiconductor substrates, such as silicon or GaAs. The optimum thickness is considerably greater than the typical membrane thickness in the work of Kevin C. Lee, J. Silcox, et al. [7]. A design being tested at the University of Massachusetts is shown in Figure 5. This design includes a cross-bar for added mechanical strength. Model experiments showed that the cross-bar has negligible effect on the radiation pattern of the element.

QUASI-OPTICAL POWER-COMBINING WITH TSA ARRAYS

Power-combining of a number of sources or power amplifiers is a promising approach to the problem of obtaining higher power output for a number of millimeter wave applications. Traditional designs employ microstrip or waveguide combining networks. If a fairly large number (10-100) of sources are to be combined, microstrip networks become very lossy at millimeter waves. We have demonstrated an active array approach, which is predicted to have an efficiency which is essentially independent of the number of elements. The combiner is intended to be used with the spacecraft transmitters in the NASA deep-space communication network, which is being extended for operation at 32 GHz. The transmitter power will first be split into a number of channels, and amplified by MMIC power amplifiers. The output from the amplifiers will be fed to the elements of a phased array, designed with TSA (Tapered Slot Antenna) radiators. The array thus combines the power of the amplifiers, and feeds it into a near-field Cassegrain reflector system, as illustrated in Figure 5. Circular polarization will be obtained from the linearly polarized array via a polarizer, indicated in Figure 5. The array is also designed for scanning ($\pm 10^o$) by incorporating MMIC phase-shifters in each channel – the corresponding scan for the reflector system is $\pm 1^o$.

The optimum element spacing depends in an array of this type on a number of factors, such as the optical system, packing density of the MMIC chips, etc. A spacing of $d = 1.22\lambda_0$ has been chosen based on such considerations. Element 3 dB beamwidths of $30–40^o$ are being used to effectively cut down the grating lobes which arise at this spacing. We have studied the predicted array directivity which can be achieved when elements with ideal $(\cos\theta)^q$ active element patterns are used. The array directivity has been calculated for a 21 element two-dimensional array configuration which is presently being developed. The predicted directivity (D) should be compared with the maximum directive gain (G_{max}) allowed by the total array area for a given element spacing. The area efficiency can be defined as $\eta_A = D/G_{max}$, and is plotted in Figure 7. It is clear that very high area efficiencies are feasible.

A transition to microstrip has been developed for the TSA elements as shown in Figure 7. One of the several substrates (10 mil Duroid 5880) which are used in the two-dimensional array is shown. Dummy TSA elements are used as edge elements to ensure that all active elements have similar patterns.

We have tested a two-dimensional array, fed from a microstrip power divider. The measured E-plane pattern, as shown in Figure 8, is very close to the predicted pattern.

Power-combining arrays of the above type are best used with power amplifier elements, or with injection-locked oscillators. Power-amplifiers and injection-locked oscillators are generally found to have higher output power, and have lower noise, than when a device of the same family (MESFET, IMPATT, etc.) is used as a free-running oscillator. A TSA array quasi-optical power-combiner therefore has considerable potential as a high-power millimeter wave source, which could also have low near-carrier noise. The power-divider would most conveniently be accomplished by using quasi-optical techniques, as shown in Figure 9. Such a power-combiner could be a convenient future source of THz power, especially if the active devices could be fabricated monolithically.

TWO-DIMENSIONAL ELECTRON GAS ELEMENTS FOR MIXING AND HARMONIC GENERATION

While both SIS and Schottky-barrier ixer diodes have been integrated with TSA elements, we would like to emphasize a more novel type of integrated receiver which uses the nonlinear characteristics of an element which is essentially a HEMT device without the gate, i.e. a two-terminal device. As in the HEMT, the current is carried by the two-dimensional electron gas (2 DEG) in a quantum well, which has been formed near a heterojunction. The structure of the device is shown in Figure 10. The microwave equivalent circuit essentially consists of a nonlinear resistance. Due to the two-dimensional nature of the electron gas, the microwave resistance will be independent of the area of the element, if the length/width ratio is held constant. Conversely, the resistance may be tailored by changing the length/width ratio. A typical device size may be of the order of 10-20 micrometers, and it is clear that the capacitance of such a device will be much smaller than for an SIS or Schottky-barrier element. The latter have to be made extremely small, in order to operate in the THz region.

The nonlinearity of the resistance arises because increasing RF power heats the electron gas above the lattice temperature; this in turn causes a change in electron mobility. This type of nonlinearity was first utilized in the InSb "hot-electron" detector and mixer. Its main disadvantage has always been the slow response time of the electrons in InSb, about 1 microsecond, which limits the IF frequency to 1 MHz. The response time of the 2DEG is much faster, of the order of .1 to 1 nanoseconds, which should result in a mixer with bandwidth in the range 1 – 10 GHz, as first pointed out by Smith et al. [8]. We are presently fabricating elements of this type for use in mixers, which could be extended to the THz region. A design in which a 2DEG element is integrated with a TSA antenna is shown in Figure 11. The original proposal for a 2DEG mixer by Smith et al., was for a liquid-helium temperture device, tuned to cyclotron resonance by a magnetic field. We have also shown that a nonlinear device at temperatures of 50–80 Kelvin, wihtout a magnetic field, should be feasible [Yngvesson, Lau and Yang, to be published]. It is also clear that the nonlinearity could be employed for harmonic generation, as well as mixing.

CONCLUSION

We have shown in this paper that TSA antenna arrays can be used with high efficiency in focal plane imaging as well as power-combining systems. The prototype systems so far have operated in the 30-100 GHz range. It appears entirely feasible to extend these prototypes to the THz range, however, and much of the interesting work in the area of integrated TSA arrays in the next few years is likely to be concentrated on such efforts.

References

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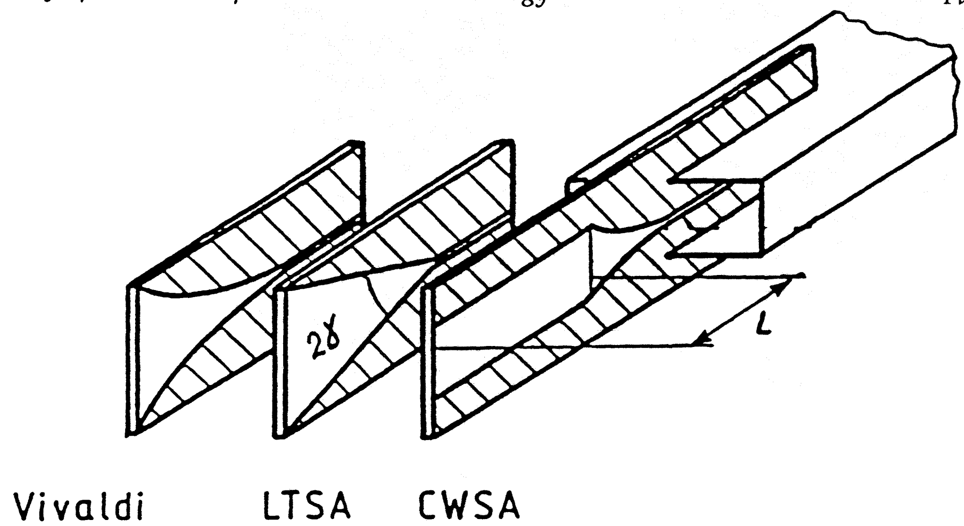


Figure1. The three different types of end-fire tapered slot antennas (TSA)

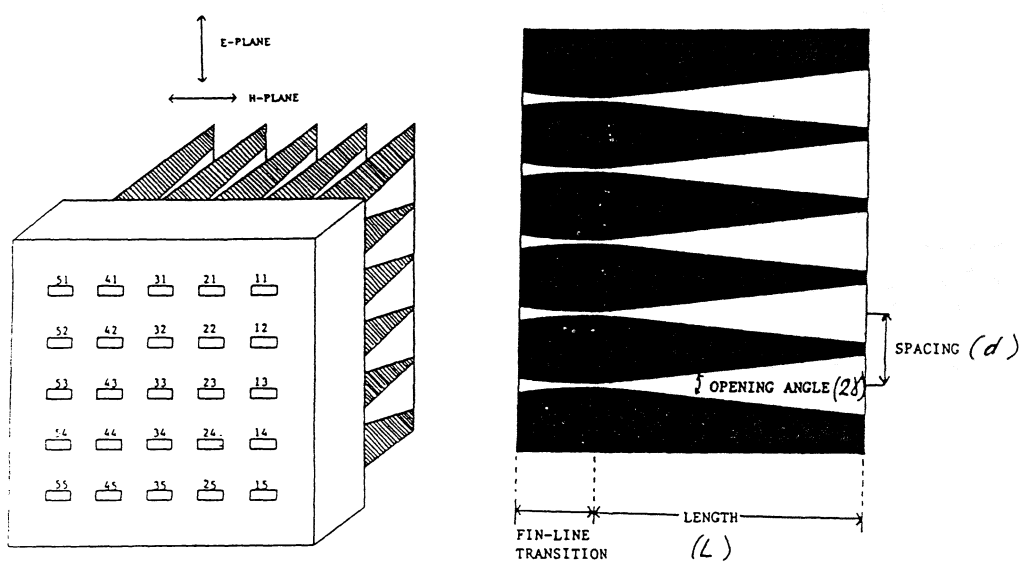


Figure 2. A typical TSA array with a fin-line to waveguide feeding block. The metal pattern made on one of the substrates is shown to the right.

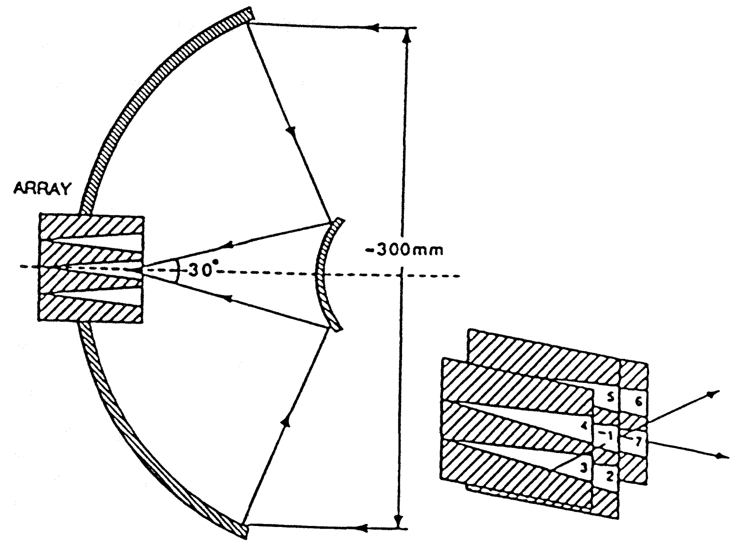


Figure 3. Schematic diagram of 94 GHz seven-element imaging system.

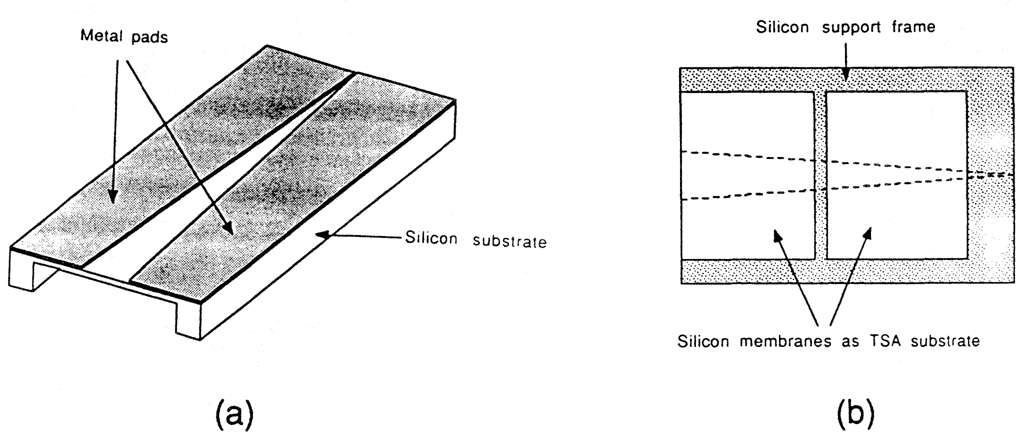


Figure 4. Silicon membrane TSA. (a) Metal pattern side; (b) Membrane side.

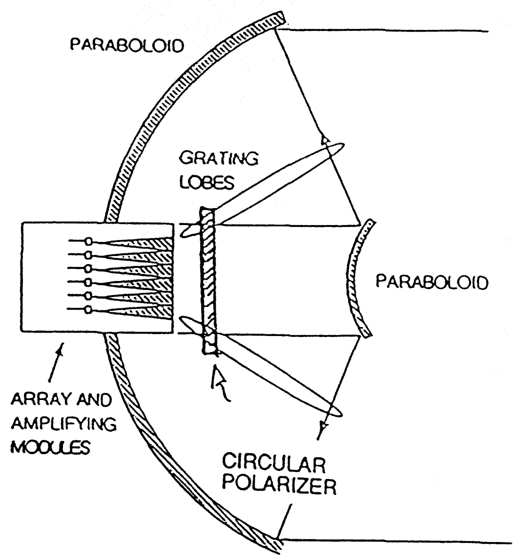


Figure 5. Overview of near-field Cassegrain reflector system with power-combining array.

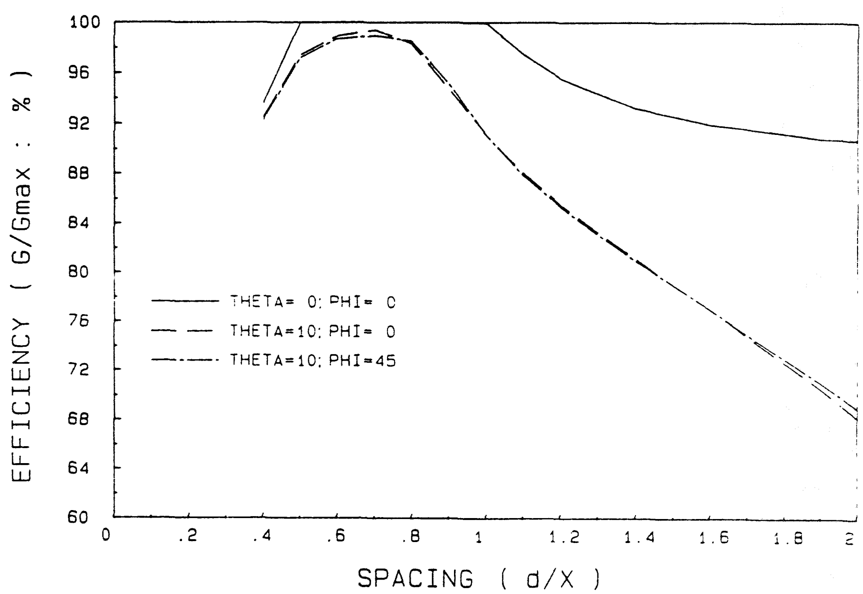


Figure 6. Calculated area efficiency of 21 element array, employing elements with $(\cos\theta)^q$, as a function of element spacing (d/λ_0). The value q has been chosen to result in maximum allowed directive gain for each element, based on its area.

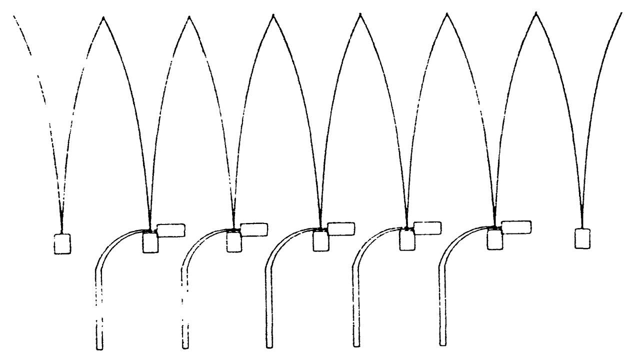


Figure 7. Slot-line to microstrip transition used in TSA array.

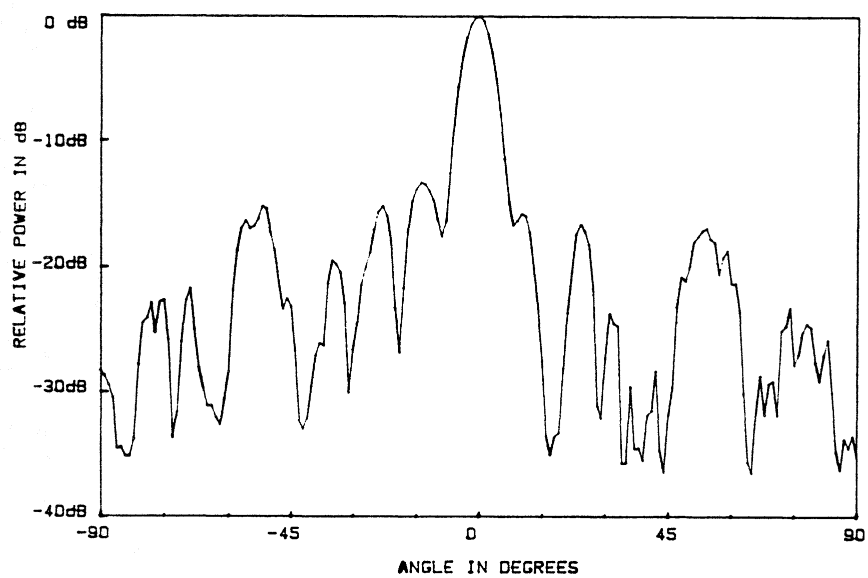


Figure 8. Measured E-plane radiation pattern for a 21-element array.

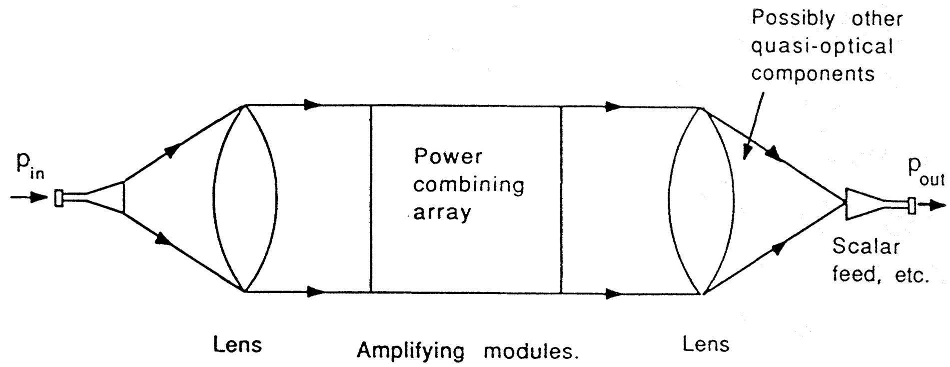
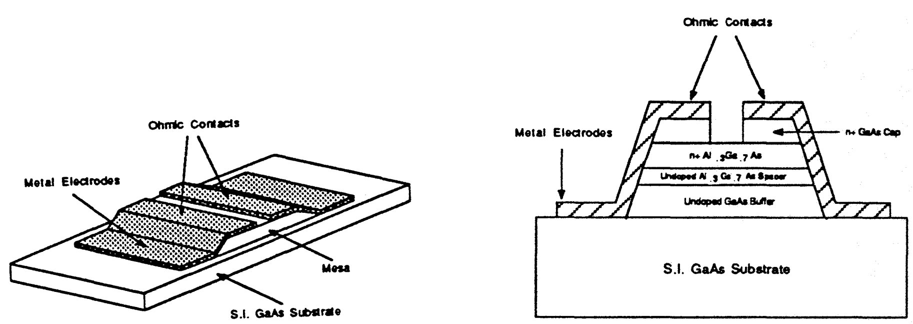


Figure 9. Schematic diagram of a focussing power combining quasi-optical system.



(a) (b)

Figure 10. Schematic diagram of a 2DEG device element. (a) overview; (b) cross section.

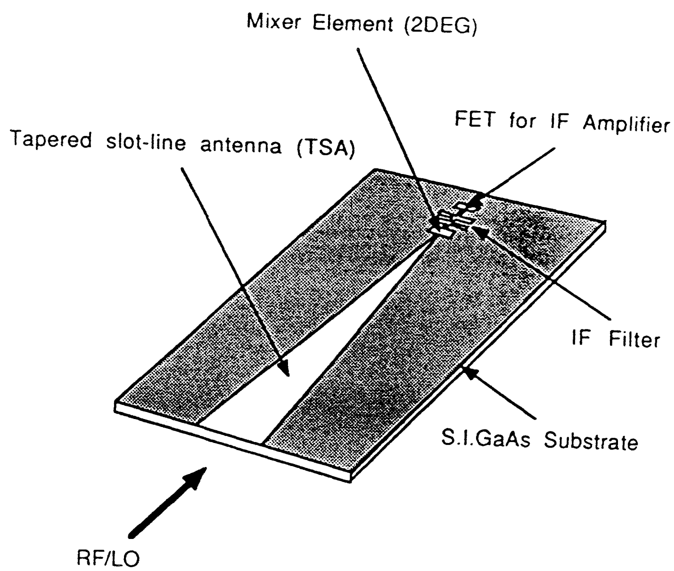


Figure 11. Monolithic millimeter / submillimeter wave TSA mixer with IF amplifier.