FINLINE COMPONENTS

COMPONENTS, FINLINE

MILLIMETER-WAVE COMPONENTS, FINLINE

E-PLANE COMPONENTS

Finline has been intensively investigated since 1970 as a planar transmission-line medium for millimeter-wave components. The electromagnetic wave is guided by slots in a metallization printed on a thin dielectric substrate. All passive circuit functions are realized by these slot-line structures, partly in combination with other types of planar transmission lines, such as microstrips or coplanar line, printed on the same substrate. These circuits are correctly known as *E*-plane circuits, but the terms finline and *E*-plane circuits are often used interchangeably. Semiconductor devices, preferably beam-lead devices, are easily soldered, glued, or bonded across the slot. The complete transmission line is held and shielded by a metal housing which most often has the (inner) dimension of the respective metal waveguide (Fig. 1). The transition from metal waveguide to finline is achieved by tapering the finline slot to the waveguide height as shown in Fig. 1. Therefore, finline components are easily combined with waveguide circuits. Because the circuit functions are determined by the planar structure, the tolerance requirements for this housing are considerably relaxed thus it is fabricated by low-cost methods like metal casting or even plastic injection molding followed by metallization.

Because of the relatively large transmission-line cross section, finline losses are typically lower than microstrip or coplanar lines, but higher than metal waveguide. Typical finline types, cross sections, and propagative properties are described in detail in (1).

PASSIVE FINLINE COMPONENTS

Filters

Finline filters, especially band-pass and low-pass filters are based on transmission line structures (2). Band-pass filters are typically realized using side-coupled [Fig. 2(a)] or end-coupled [Fig. 2(b)] resonators. To reduce losses, end-coupled filters may degenerate to pure *E*-plane waveguide filters, as shown in Fig. 2(c). In this case, the "slot width" is equal to the waveguide height, and no taper to waveguide is necessary. Even the dielectric substrate material may be omitted, resulting in simple metal insert filters. For better stop-

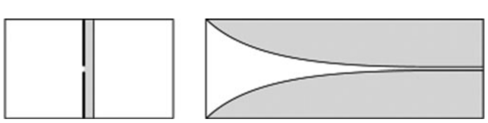

Figure 1. Cross section of a (unilateral) finline and metallization pattern for a transition from waveguide to finline.

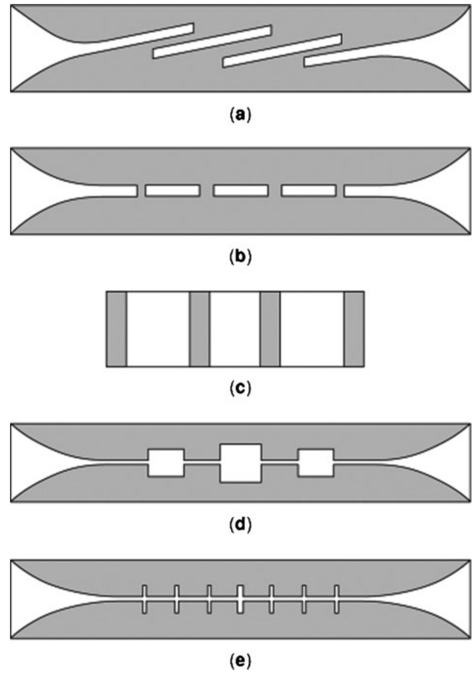

Figure 2. Typical metallization patterns of different finline filters. (a) Side-coupled bandpass filter. (b) End-coupled bandpass filter. (c) End-coupled bandpass filter. The slot width has been increased to the waveguide height, losses are lower, and no taper to waveguide is required. (d) High-low impedance low-pass filter. (e) Stub-type low-pass filter.

band attenuation, bilateral finline or several metal inserts side-by-side are used. These arrangements strongly suppress higher order mode coupling and therefore improve stop-band behavior. Detailed descriptions of these kinds of filters, together with diplexers, are presented by Shih et al. (3) and Dittloff et al. (4).

Low-pass filters are typically based on low- and high-impedance line sections [Fig. 2(d)] or stub structures [Fig. 2(e)]. High impedances are easily realized with wide slots. For uniplanar finline, the lowest impedance value is determined by the minimum slot width which can be technologically realized. For bilateral or antipodal finline, overlapping of the metallization further reduces the characteristic impedance of the respective line segment. The discontinuities involved have to be included in the design procedure, especially for large impedance steps.

Directional Couplers

The design of a directional coupler in conjunction with finline was first reported by Meier (8) based on printed metal probes between two adjacent metal waveguides, placed in between two thin substrate layers in the *E*-plane. Finline couplers, however, are mostly designed on the basis of coupled slots. Such a coupled transmission line structure supports two modes, one similar to the normal finline mode with the electric fields in the same direction, the other one a coplanar type mode with zero cutoff frequency. One coupler design, shown in Fig. 3(a), relies on a quarter-wave section of coupled lines. The fundamental principles of operation are comparable to respective couplers in mi-

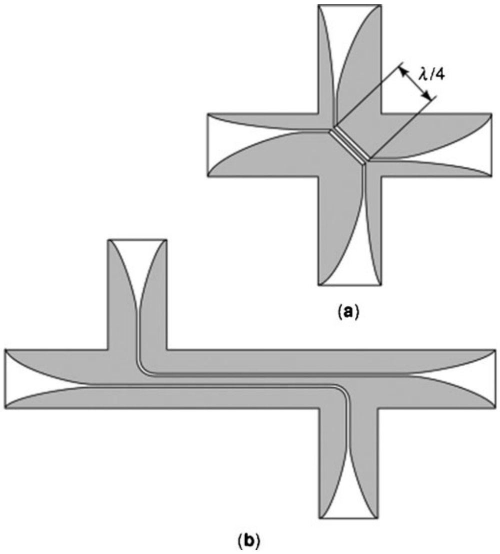

Figure 3. Metallization patterns of two different finline couplers.

crostrip or microstrip/slot-line techniques. The center strip may alternatively be replaced by a bond wire, or the metallization section containing the strip may be placed on the backside of the substrate (antipodal finline), thus achieving increased design flexibility. Another coupler principle is based solely on the different phase velocity of the two modes on the coupled transmission line [Fig. 3(b)]. Feeding a wave to one of the ports, an increasing part of the electromagnetic field couples from one slot to the other with increasing propagative distance, that is, the amount of coupling depends on the length of the coupled line section. This length is several wavelengths, but in the millimeter-wave range, this is normally not a big problem because of the short wavelength. In contrast to the first type of coupler, a smooth transition from the feeding line to the coupled line section with minimum reflections is mandatory. With both types of couplers, broadband performance over a complete waveguide band is achieved (5–7).

Nonreciprocal Components

Some effort has been made to develop circulators and isolators in finline or by a compatible *E*-plane technique. A ferrite sphere or a small cylinder is placed in the center of a finline Y-junction to realize circulators (9, 10). For a field displacement type of isolator, an additional layer of ferrite substrate together with an absorbing sheet is added to the finline on a standard substrate (11). Optimization is done by full-wave calculations of the composite structure. Both approaches, however, lead to rather complex and therefore mechanically sensitive structures, so these are not used in practical applications.

A more successful approach is the realization of waveguide type circulators in a metal waveguide, Y-junction in the *E*-plane (12). A ferrite disk is placed in the junction. The diameter of the disk is equal to the inner diameter of the waveguide Y-junction. The center frequency is determined by the height of the disk. A permanent magnet is placed in a hole in the waveguide mount close to the ferrite disk.

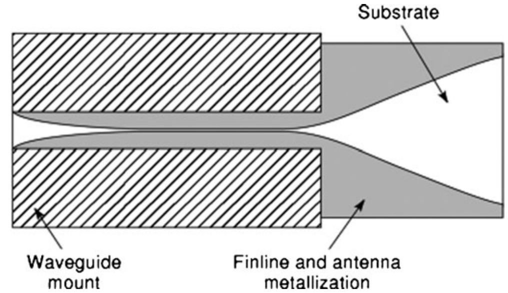

Figure 4. Waveguide mount and metallization pattern of a finline antenna. The planar substrate with the finite metallization protrudes out of the waveguide mount and acts as a slotline type antenna.

This type of circulator, therefore, is fabricated easily, and it is integrated into the *E*-plane split block together with single or integrated finline components, as shown later on. Circulators of this type are even built up to the 140 GHz frequency range.

Finline Antennas

Extending the finline substrate out of the waveguide mount allows the realization of slot-line or "Vivaldi" type end-fire antennas (Fig. 4). Beam form, sidelobe level, and bandwidth are determined, to some extent, by the form of the tapered metallization structure and by a proper choice of the substrate thickness and its dielectric constant. Beam width, however, remains relatively wide associated with a low gain. The advantage of finline antennas is integrating several antennas as a feed cluster to form multiple beams in conjunction with lens or reflector antennas (13).

DIODE-BASED FINLINE COMPONENTS

Schottky diodes, *p–i–n* diodes, and varactor diodes have been fabricated as beam-lead devices for many years and are ideally suited for integration into finline circuits. Because of their low parasitic capacitances and inductances, high-performance components with wide bandwidths can be built.

Detectors

For a finline detector, a low-barrier Schottky diode is placed across the finline slot. One of the finline metallizations has to be isolated from the metal mount by a thin dielectric sheet (10 to 20 μm). Alternatively, an oxidized aluminium mount is used. For broadband operation, some absorber material is placed behind the diode. Figure 5 is a sketch of the detector layout. Detectors of this type are capable of zero-bias operation over one or two waveguide bands with sensitivities of several hundred mV/mW, and they are even designed for frequencies up to 200 GHz and above (7, 14).

p–i–n-Diode Attenuators and Switches

In the same way as with the detector, one or more beam-lead *p–i–n* diodes are easily placed across a finline slot. With bias applied to the *p–i–n* diodes, these exhibit a low series resistance together with some parasitic inductance.

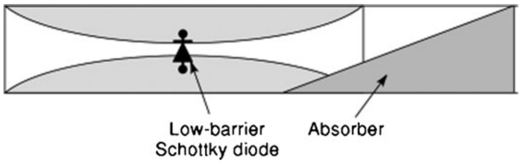

Figure 5. Basic setup of a finline detector. One of the finline metallizations is dc isolated from the waveguide mount to allow the extraction of the rectified output signal.

Thus they basically short-circuit the finline slot. Without or with reverse bias, *p–i–n* diodes load the finline slot only with their fairly low capacitance. Basically, two types of attenuators or switches have been developed. The first one uses diodes in a shunt configuration shown in Fig. 6(a). Placing two or more diodes approximately a quarter wavelength apart results in some compensation of the diode capacitance in the onstate of the switch, that is, without biasing the diodes. Attenuators (the attenuation is controlled by the amount of diode bias) or switches of this type typically have an insertion loss of 0.5 dB in the Ka-band (26 to 40 GHz) up to 1.5 dB in the W-band (75 to 110 GHz) over a nearly complete waveguide band.

Maximum attenuation amounts to about 15 dB per diode. For attenuation values higher than about 50 dB, some attention has to be paid to parasitic power leakage along the dc isolation between metallization pattern of the substrate and the waveguide mount, and absorbing isolating foils must be used to prevent this. For attenuators operating over even two waveguide bands, the finline is placed in a ridged waveguide mount.

The second type of *p–i–n* diode switch is based on a series configuration of the diode [Fig. 6(b)]. A diode is placed across a lateral slot in the metallization. This slot is short-circuited for RF signals by the wall of the waveguide mount. Together with the diode capacitance, this stub

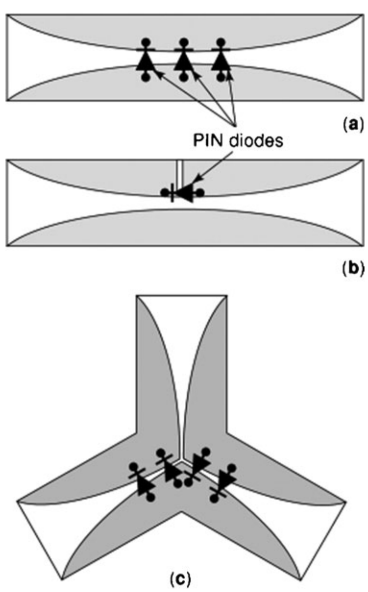

Figure 6. Metallization patterns of (a) finline shunt type and (b) series type attenuator or switch, and (c) single pole double through (*SPDT*) switch with shunt diode configuration.

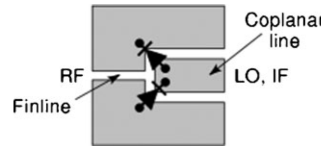

Figure 7. Basic principle of a balanced finline mixer. The combination of finline and coplanar line forms an inherently broadband 180° hybrid junction.

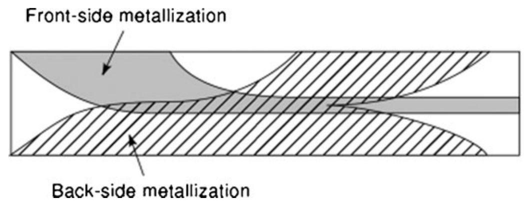

Figure 8. Layout of a transition from finline to coplanar line via an antipodal finline and a microstrip line.

forms a parallel resonator in the "off" position of the attenuator, whereas the stub is short-circuited in the "on" position. Accordingly, this attenuator has a more narrowband performance, but with increased attenuation for a single diode. Furthermore, it presents some advantages with respect to dc isolation from other components in integrated finline circuits. In the case of a single diode, the metallization at only one side of the stub has to be dc isolated from the waveguide mount. With two cascaded structures of this type, only the metallization between the stubs needs to be dc isolated (also see section on integrated finline components).

Two or three switches previously described, preferably those with diodes in a shunt configuration can also be arranged for single-pole, double-throw (*SPDT*) or single-pole triple-throw (*SP3T*) switches, as shown in Fig. 6(c). This results in performance similar to the single switches except for slightly increased losses due to the additional transmission-line(s) loading. Further details and numerous results are described in (15).

Finline Mixers

Although single-ended mixers are easily realized by placing a beam-lead Schottky diode across the finline slot (8), much more effort has been put into the design of a balanced mixer based on a combination of finline and coplanar line, as shown in Fig. 7. This structure is an ideal combination for forming an inherently broadband, 180°, hybrid junction. The Schottky diodes are placed across the junction, in series with respect to the finline and antiparallel with respect to the coplanar line. The RF signal is fed to the diodes via the finline, and the local oscillator (*LO*) signal via the coplanar line. Then the intermediate frequency (*IF*) is also extracted from the coplanar line. Therefore, some diplexing circuit must be added to the coplanar line. This single balanced mixer design has inherent high mutual isolation between RF and LO ports (and RF and IF ports, respectively), but in practice this is limited due to asymmetrics in the circuit structure or the diodes.

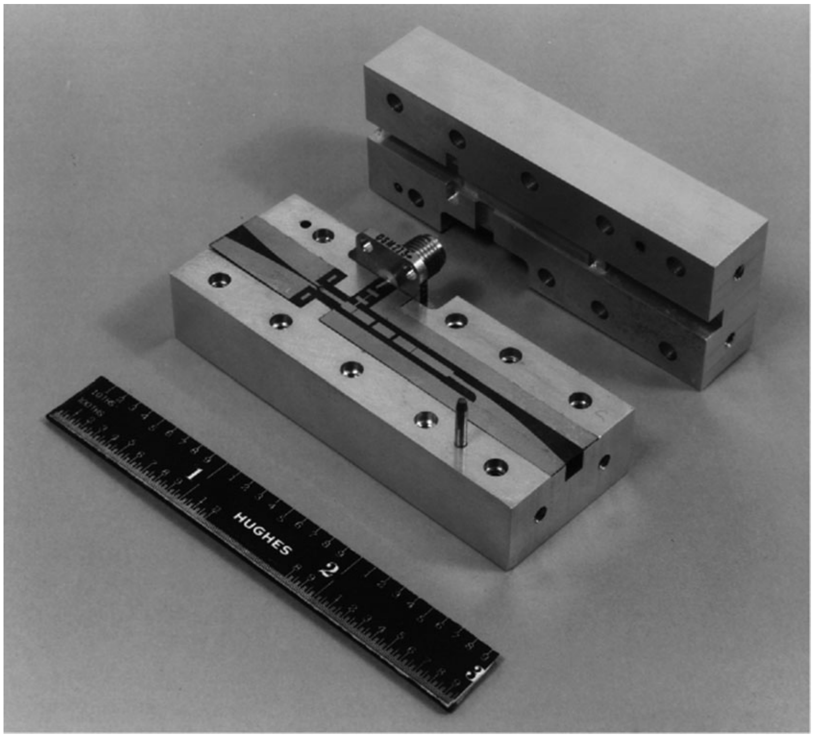

Figure 9. Photograph of a Ka-band balanced finline mixer (16), courtesy of Academic Press).

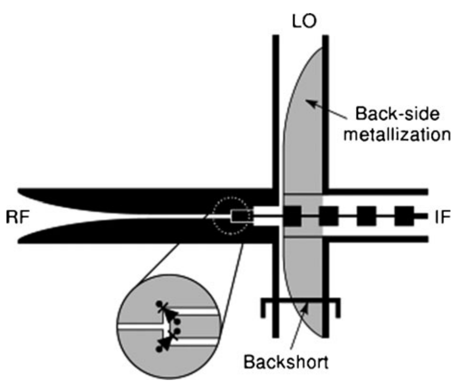

Figure 10. Basic layout of a balanced finline mixer with probe-type transition to coplanar line (18).

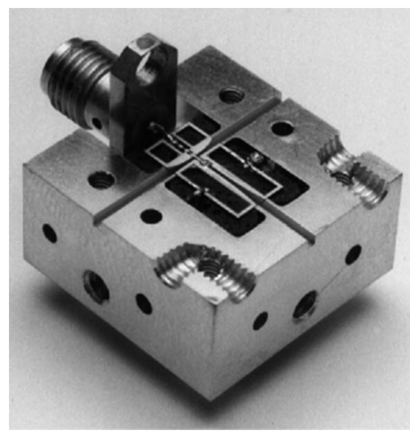

Figure 11. Photograph of a 140 GHz finline mixer (18). The waveguide mount is opened, and the quartz substrate with the mixer circuitry clearly can be seen.

Many mixers based on this configuration have been developed. Basic differences were found mainly in the LO/IF feeding arrangement. Some mixers use a transition from finline to coplanar line via an antipodal finline, as sketched in Fig. 8, possibly together with an end-coupled, band-pass filter for the LO signal and a microstrip low-pass filter for the IF. A typical Ka-band finline filter of this type was presented by (16, 17) and is shown in the photograph in Fig. 9. Another design (7, 18) uses a transition from finline to coplanar line based on magnetic coupling, as shown in Fig. 10. Very broadband performance and operating frequencies up to 150 GHz are reported (18) with this type of mixer. A photograph of a 140 to 150 GHz mixer is given in Fig. 8.

Because sufficient LO power in the millimeter wave frequency range is sometimes difficult or too expensive to generate, efforts have been undertaken to design subharmonically pumped mixers. For mixing with even harmonics of the LO frequency, two diodes are used in an antiparallel configuration. For old harmonics, a circuit and diode configuration as used for the balanced mixer and shown in Fig. 7 are employed. Together with suitable filter configurations (Fig. 12), mixers with a LO frequency at about half the RF frequency (19, 20) and at much lower frequencies, for example $f_{\mathrm{LO}} \approx f_{\mathrm{RF}}/8$ (21), have been realized.

For sub-millimeter-wave applications, superconductor–insulator–superconductor (SIS) element mixers are often used. To feed both the RF and LO power to the SIS elements, an integrated transition from metal waveguide via finline to microstrip may be employed. Such solutions are reported up to 700 GHz (22, 23).

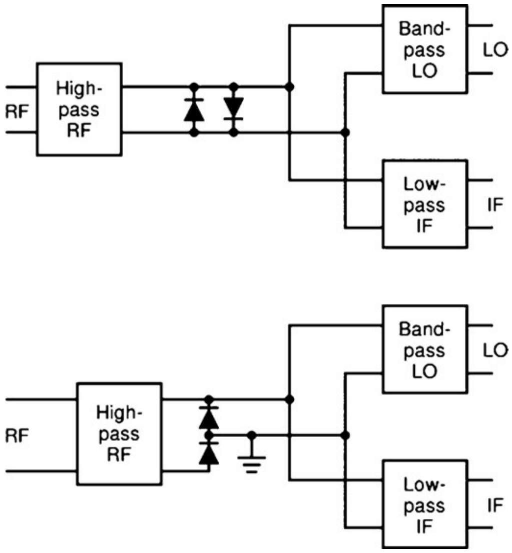

Figure 12. Basic block diagrams of harmonic mixers. For even harmonic mixing products, an antiparallel diode configuration is used, for odd mixing products, a parallel/antiparallel diode arrangement is preferred.

Phase Shifters

Finline phase shifters are based on two different principles. The first uses a 3-dB coupler described earlier in this chapter together with *p–i–n*-diode switches to modify the two output port loads (6). The other principle uses a configuration similar to that of the balanced mixer [see Figs. 7 and 10 and (24, 25]. For the phase shifter, either *p–i–n* or Schottky diodes are alternately switched "on" or "off" via a bias applied to the coplanar line. With an appropriate matching of the circuitry, signal transmission between the finline port (RF port in the mixer case) and the coplanar port (LO port of the mixer) undergoes a phase difference of 180° depending on the sign of the control voltage, that is, depending on which diode is in the "on" (biased) state.

A third approach uses electrically controllable materials like barium-strontium-titanate (BSTO) or liquid crystal material (26, 27) to adjust the phase constant in a transmission line. The space between the overlapping metallizations of an antipodal finline can be filled with e.g. liquid crystal material, while a dc voltage between the two fins controls the dielectric constant of the material and thus the overall phase shift of the respective transmission line section (27).

Frequency Multipliers

As the generation of power in the millimeter-wave frequency range is getting increasingly difficult with increasing frequency, frequency multiplication using varactor or even Schottky diodes is of great interest, too.

A combination of coplanar line and finline, as it is used for balanced mixer applications (Fig. 7) can be employed for frequency doubling. The fundamental frequency signal is fed to the coplanar line, and the harmonic signal is extracted from the finline (the underlying principle is very similar to that of a balanced rectifier). In (28), such a configuration is described for a frequency doubler from the 20 to 25 GHz to the 40 to 50 GHz frequency range. Finite difference time domain (FDTD) calculations were used to optimize and match the structure for this relatively wide bandwidth, taking into account the nonlinear behavior of the employed Schottky diodes with respect to their actual position in the coplanar-finline junction.

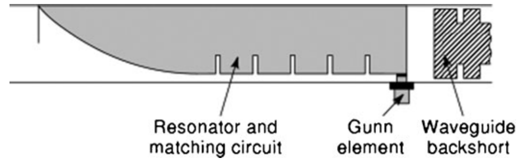

Figure 13. Basic setup of a finline Gunn oscillator. The Gunn element is screwed directly into the waveguide mount; resonance and matching structures are integrated into the planar structure.

A different approach is selected in (29) where a large number of heterostructure barrier varactor (HBV) diodes are placed across a unilateral finline forming a nonlinear transmission line (NTL). In this way, a frequency tripler is realized for the 130 GHz output frequency range.

FINLINE OSCILLATORS AND AMPLIFIERS

A number of efforts have been made to realize oscillators by the integrated finline technique. A basic problem is always heat removal from the active elements. Therefore, Gunn elements are mostly used screwed directly into the broadside of the waveguide mount. Then the diode cap is soldered directly to one side of the finline metallization which contains the necessary resonance and matching circuits (Fig. 13). Final tuning is typically done with a backshort in the metal waveguide behind the diode. A more detailed review of finline oscillators is given in (30). Although some oscillators are used in integrated finline front ends (see next section), they have not proven suitable for high-volume and low-cost applications.

A number of authors published designs of "finline" amplifiers (31, 32). Their arrangements, however, are microstrip FET amplifiers with transitions to finline, and they use the waveguide mount as some kind of package and radiation shielding.

Recently, power combining in an (oversized) metal waveguide using finline has gained some interest. To this end, two or more finline slots are placed side by side on one substrate (32), each finline slot connected to an amplifier, typically via a transition to microstrip. In addition, several substrates may be placed at several positions in the *E*-plane as indicated in Fig. 14 (e.g. 33,34). Power combining is then accomplished either in the connected metal waveguide, or the power is radiated and combined in free space using a lens or reflector arrangement.

INTEGRATED FINLINE COMPONENTS AND FRONT ENDS

The major advantages of planar components are exploited by integrating several components to "supercomponents" or complete front ends. With respect to finline, this is

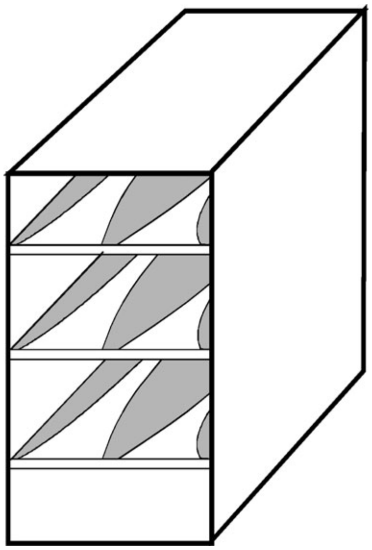

Figure 14. Finline configuration with multiple parallel slots and multiple substrates.

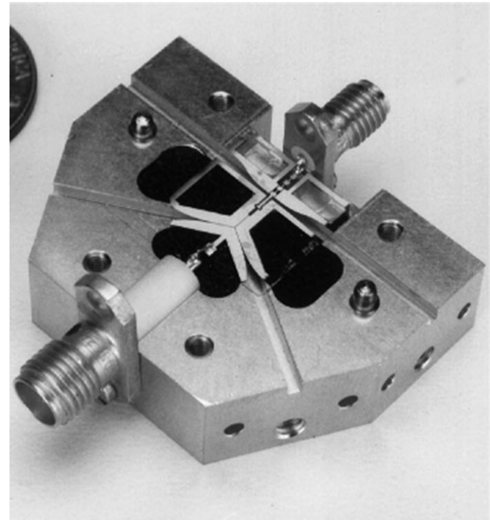

Figure 15. Photograph of a 94 GHz integrated finline circuit including a balanced mixer and a *p–i–n*-diode SPDT. The waveguide split block is opened to see the quartz substrate with the planar circuit.

done in two different ways. Because finline circuits consist of planar circuits and waveguide mounts, a first step is to integrate several finline circuits in a single waveguide mount, although each circuit still has its own transition(s) to waveguide. This concept allows optimizing and testing all finline circuits separately and combining them with waveguide circuits like oscillators, waveguide filters, or circulators realized in a waveguide mount split in the *E*-plane. The complete waveguide mount if fabricated by computer-controlled milling or, for high production quantities, by plastic injection molding combined with an appropriate metallization technique. Some disadvantages of this arrangement are increased losses due to the repeated tapers from waveguide to finline and possibly some problems with the interaction of components over larger distances causing an increased ripple in transmission and return loss behavior. Integrated front ends of this type have been realized for communication equipment in the Ka-band (35), for military surveillance receivers (36), and for radar front ends for military seeker heads (37) and automotive radar for intelligent cruise control (38). For example, in (35) a transmitter front end for a 29 GHz communication system includes an *E*-plane waveguide circulator, two couplers, a *p–i–n*-diode biphase modulator, and a *p–i–n*-diode attenuator. The power is generated by an external Gunn oscillator. An *E*-plane, metal insert, band-pass filter is added to this unit with an additional waveguide mount.

An even higher degree of integration is achieved by integrating several components on a single substrate with direct finline interconnects, that is without transitions from finline to waveguide and back to finline. In this way, much smaller components with reduced losses result. Furthermore, the single components are placed close together thus avoiding strong phase variations from mutual interactions as a function of frequency. On the other hand, the single components in such a supercomponent can no longer be tested separately.

A number of integrated front ends of this type have been realized by the author and his group, starting with the integration of balanced mixer and *p–i–n*-diode attenuators acting as a sensitivity time control (*STC*) for radar applications or as a Dicke switch for a radiometer (39).

Figure 15 shows the opened waveguide mount with a quartz substrate containing a 94 GHz mixer and a SPDT switch. Two diodes in each of the two input arms of the circuit are mounted with opposite polarity. Thus only a single control input for the Dicke switch is necessary. Efforts were also made to integrate Gunn oscillators as shown previously (Fig. 13). In (39), the integration of a mixer with a two-diode series type of *p–i–n*-diode attenuator [Fig. 6(b)], and a Gunn oscillator as a LO is demonstrated (see the photograph in Fig. 16). In this example, the series type of *p–i–n*-diode attenuator is used favorably for bias isolation only the finline metallization between the two stubs loaded with the diodes must be dc isolated.

Even the integration of a Ka-band pulse radar sensor on a single substrate including pulse oscillator and LO, an SPDT switch as a transmit/receive switch, a series type *p–i–n* diode STC, and a balanced mixer was demonstrated (40).

For a 94 GHz dual polarization radar, an integrated receiver front end was realized using both an integrated finline circuit (2 mixers, 2 *p–i–n*-diode STCs, and a power divider on a single substrate) and waveguide components (*E*-plane circulator, *E*-phase metal insert filters, and a turnstile coupler) (41). Figure 17 shows a block diagram of the front end. Figure 18 shows the two receiver conversion loss curves. They include the conversion loss of the mixers and the insertion losses of *p–i–n*-diode attenuators, the *E*-plane filters, and the *E*-plane circulator. The overall system noise figure amounts to 12 dB.

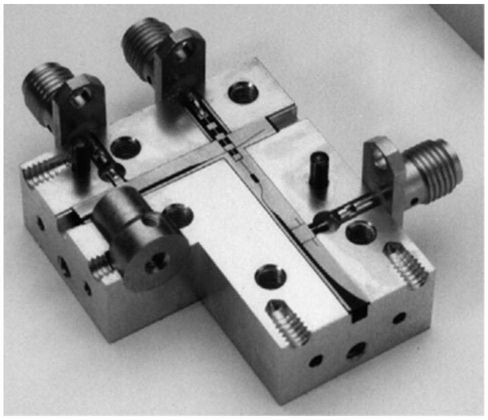

Figure 16. Photograph of a 60 GHz integrated finline receiver consisting of a Gunn oscillator as an LO, a balanced mixer, and a series type *p–i–n*-diode attenuator. The Gunn element is screwed into a copper heat sink in the waveguide mount; the series *p–i–n*-diode attenuator allows a dc isolation with respect to the other components.

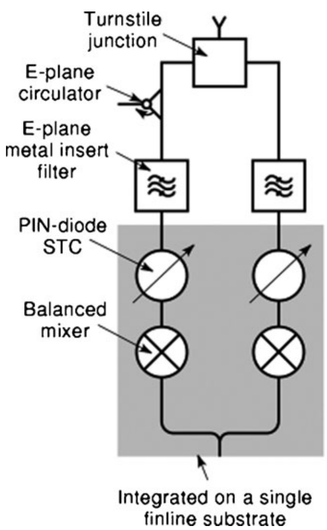

Figure 17. Block diagram of an integrated, dual-channel 94 GHz radar receiver front end. All components (except for the turnstile junction) are combined in a single *E*-plane split block mount. Balanced mixers, *p–i–n*-diode STC's and the LO power divider are integrated on a single substrate.

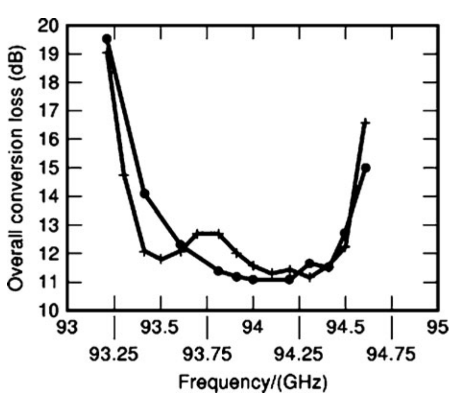

Figure 18. Overall conversion loss of the two channels of the 94 GHz radar receiver (see Figure 17).

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