Multimode Hybrid Junctions

M. Hamid
Department of Electrical and Computer Engineering
University of South Alabama
Mobile, Alabama 36688, U.S.A.
mhamid@usouthal.edu

Abstract: The design, construction and testing of new hybrid junctions to perform the usual functions of summation and subtraction of incoming signals, not only over the fundamental mode but also to include the first few higher order modes, are important tasks for both military and civilian applications. The performance of the proposed junctions is evaluated experimentally and their relevance for a variety of microwave measurements and tracking radars suggested.

Keywords: Microwave Hybrid Junctions, Radar, Higher Order Modes

1. Introduction

Hybrid junctions or combining circuits are primarily magic tees, hybrid rings and directional couplers that are employed in a variety of electromagnetic engineering applications for duplexing and mixing of signals as well as impedance measurements. They are also used for signal sampling as well as amplitude-phase bridge networks for on-line monitoring and quality control of physical and dielectric properties of sheet materials during the manufacturing and processing stages [1-2].

The operation of these junctions is based on the principle that analog signals incident at some ports are added in or out of phase at other "sum" and "difference" ports, respectively. Thus it is possible to redirect signals to some ports and isolate others. This is particularly important in radar systems as will be discussed later.

Applying the reciprocity principle to the four port magic tee shown schematically in Fig. 1a, we see how signals incoming at the collinear ports 3 and 4 add in phase at port 1 (parallel arm or P arm) and out of phase at port 2 (shunt arm or S arm). Conversely, a signal fed into port 1 splits equally between ports 3 and 4 with the outputs equal in amplitude and opposite in phase. On the other hand, a signal fed into port 2 also splits between ports 3 and 4 with the outputs equal in amplitude and phase. Thus two transmitters with equal power connected to ports 2 and 1 will produce twice as much power at port 4 and none at port 3.

The hybrid ring shown in Fig. 1b operates on similar principles where signals add in phase if they are an even number of half waveguide wavelengths ($\lambda_g/2$) apart and out of phase if they are an odd number of half waveguide wavelengths ($\lambda_g/2$) apart. With a signal fed into port 1, two outputs with equal amplitude and opposite phase will appear at ports 3 and 4 and zero output at port 2. On the other hand, a signal fed into port 2 produces two signals of equal amplitude and phase at ports 3 and 4 and cancels out at port 1. Also a signal fed into port 3 splits with equal amplitude and phase at ports 2 and 1, and no signal appears at port 4. Similarly, a signal fed into port 4 splits with equal and opposite phase at ports 1 and 2 and no signal appears at port 3.
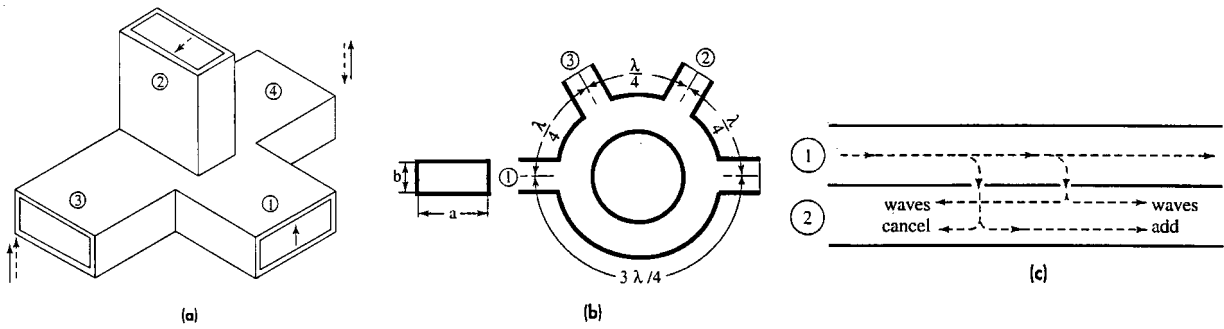
Figure 1. Schematic Diagram of Four-Port Hybrid Junctions.
(a) Magic Tee (b) Hybrid Ring (c) Directional Coupler

The two hole directional coupler shown in Fig. 1c has two identical sampling holes between the primary and secondary waveguides so that forward signals add in phase at port 4 and cancel in port 2, and so on.

The disadvantages of all three hybrid junctions in the rectangular waveguides shown in Fig. 1 is the residual or leakage coupling between the collinear arms which are supposed to be isolated from each other at the design frequency or within the passband of the waveguide. At frequencies higher than the design frequency, but still above the cutoff frequency f_c of the fundamental TE or TM mode of the waveguide, this coupling increases so dramatically that the "magic tee" loses its "magic power". In such

cases, higher order modes are excited in all three types of hybrid junctions, and a solution needs to be found for both rectangular and circular waveguide hybrid junctions.

The problem of redesigning hybrid junctions to perform analog sum and difference signals over the fundamental as well as higher order modes is very critical in certain types of tracking radars which are described in detail elsewhere [3]. As a review example, the conventional amplitude-comparison monopulse tracking radar for a single angle coordinate employs two squinted antenna feeds which are connected to a magic tee so that the sum (Σ) and difference (Δ) signals appear at the two output ports as shown in Fig. 2, [3]. On reception, the outputs of the sum and difference
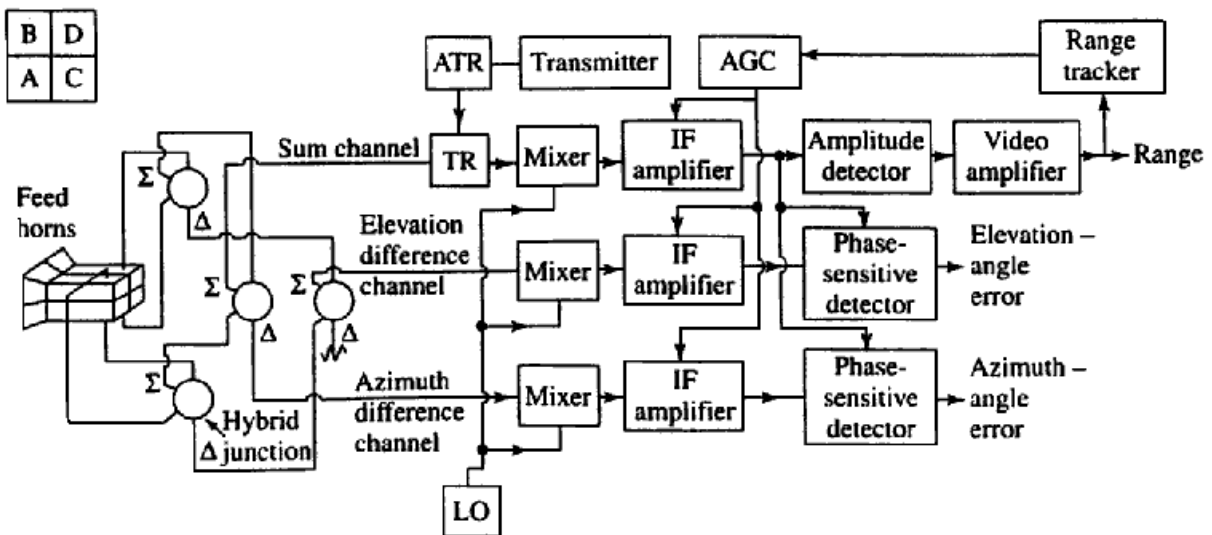

Figure 2. Schematic Diagram of Two-Coordinate (Azimuth
and Elevation) Amplitude-Comparison Monopulse Tracking

ports are each heterodyned to an intermediate frequency (IF) and amplified in a super heterodyne receiver where the local oscillator (LO) is shared by the two channels which are maintained with the same amplitude and phase characteristics. The transmitter is connected to the sum port of the hybrid junction while a duplexer is inserted in the sum channel to protect the sum channel receiver. The outputs of the sum and difference channels are inputted to a phase sensitive detector which is a nonlinear device that compares the two signals at the same frequency. The output of this detector is the angle-error signal θ_q whose magnitude is proportional to the difference between the target and boresight angles, while the polarity of the output indicates the direction of the angle error relative to the boresight. This technique is extended to two-angle coordinate measurement by employing a cluster of four (A, B, C and D) feed horns (feeding a cassegrain dish or space-fed phased array) which generate four partially overlapping (squinted) beams as shown schematically in Fig. 2. The sum pattern is found from (A+B+C+D) while the azimuth difference pattern is obtained from (A+B) - (C+D) and for the elevation plane the difference pattern is found from (B+D) - (A+C). Range information is extracted from the output of the sum channel after envelope detection and is employed for range tracking.

Although the four-horn feed system is simple, it cannot provide the sum and difference patterns that are independently optimized. The sum pattern should have maximum gain on axis which requires uniform aperture illumination. On the other hand, the difference pattern should have an aperture illumination which results in a large slope of the error signal at the beam crossover. For this, some improvement has been incorporated in some precision tracking radars by using a five-horn feed consisting of one horn in the middle to produce the sum pattern surrounded by four horns to generate the difference patterns. The analysis in the literature indicates that the sizes of the four horns generating the difference pattern should be twice as big as the central horn

generating the sum pattern. Instead of further improvement by adopting a twelve-horn design to satisfy the optimization criteria and avoid complexity, it has been the practice in many types of radar to use higher order waveguide modes to obtain better control of the sum and difference patterns. An example of such systems is the AN/MPS-39 for multiple missile tracking or the MOTR (Multiple Object Tracking Radar) which employ a four–horn triple-mode feed. For these multimode feed systems and for other systems, which employ multiple frequencies or frequency agility/diversity to smooth out the angle error due to glint, it is necessary to develop new multimode hybrid junctions to produce the sum and difference patterns which is the main purpose of this paper.

2. Outline of Proposed Hybrid Junctions

The primary objective of this project is to design and develop new types of multimode hybrid junctions in rectangular and circular waveguides which permit the extraction of separate sum and difference signals for the fundamental as well as higher order TE and TM modes in multimode signals. These are shown schematically in Fig. 3 for rectangular and circular waveguides. The basic approach is to use cascaded hybrid junctions, one for each mode of interest, so that the sum and difference signals can be displayed and processed separately for each mode. Starting with Fig. 3a, we see that the collinear arms of the magic tee in the primary rectangular waveguide accommodate the fundamental as well as all the higher order modes excited above frequencies f_c relative to $(f_c)_{TE\ 10}$ of the fundamental mode. A second mode magic tee is inserted in cascade with its collinear arms coupled to the primary waveguide so as to extract the second and all higher order modes, but not the primary mode, since its dimensions are such that the primary mode is below cutoff. Only the second mode is processed in the second mode magic tee since the third and higher order modes are extracted in the third mode magic tee prior to
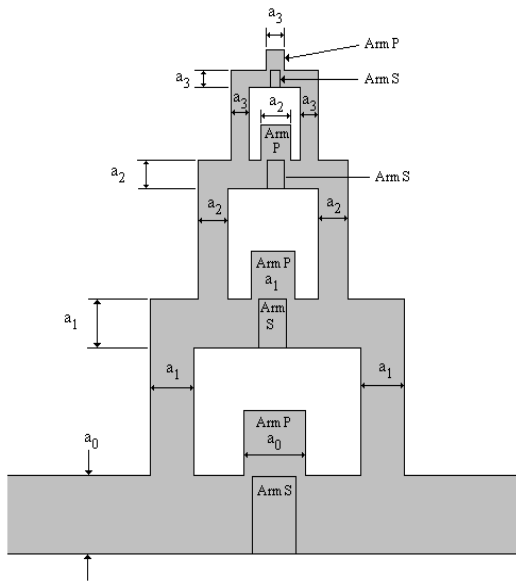
H-plane dimensions $a_0 > a_1 > a_2 > a_3$ for the parallel (P), summing arms of the magic tees

Some E-plane dimensions for the series (S), difference arms of the magic tees may be equal, depending on the mode selected. The difference arms are perpendicular to the plane of the paper.
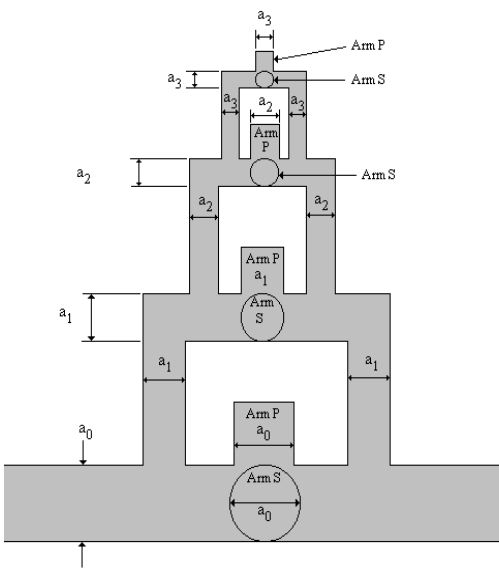
Figure 3.a. Cascaded Mode-Selective Rectangular WG Magic Tees
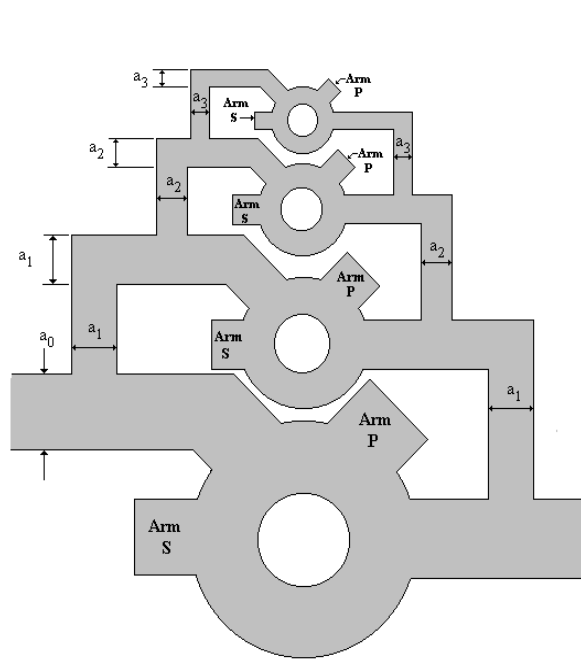
H-plane dimensions $a_0 > a_1 > a_2 > a_3$ for the parallel (P), summing arms of the hybrid junctions.
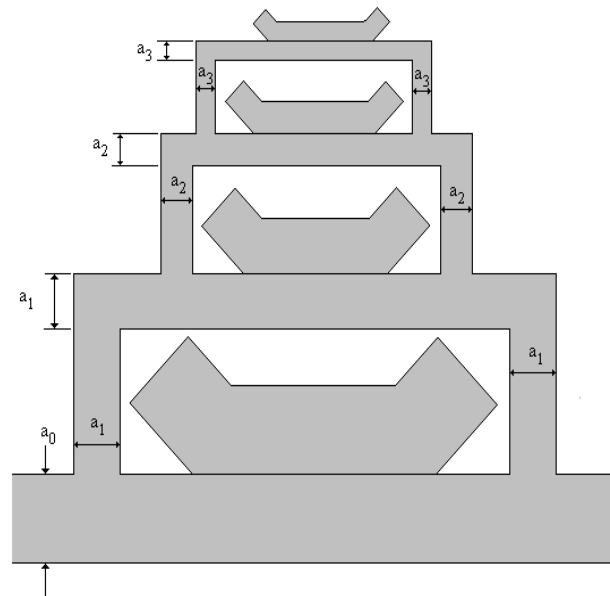
Some E-plane dimensions for the series (S), difference arms of the hybrid junctions may be equal, depending on the mode selected.

Figure 3.c. Cascaded Mode-Selective Hybrid Junctions

Diameters $a_0 > a_1 > a_2 > a_3$ provide selection of successively higher modes in a manner similar to cascading high-pass filters with successively higher cut-off frequencies.

Figure 3.b. Cascaded Mode-Selective Circular WG Magic Tees

H-plane dimensions $a_0 > a_1 > a_2 > a_3$ for the parallel (P), summing arms of the hybrid junctions.

Some E-plane dimensions for the series (S), difference arms of the hybrid junctions may be equal, depending on the mode selected.

Figure 3.d. Cascaded Mode-Selective Directional Couplers

(a) Rectangular Waveguides   (b) Circular Waveguides
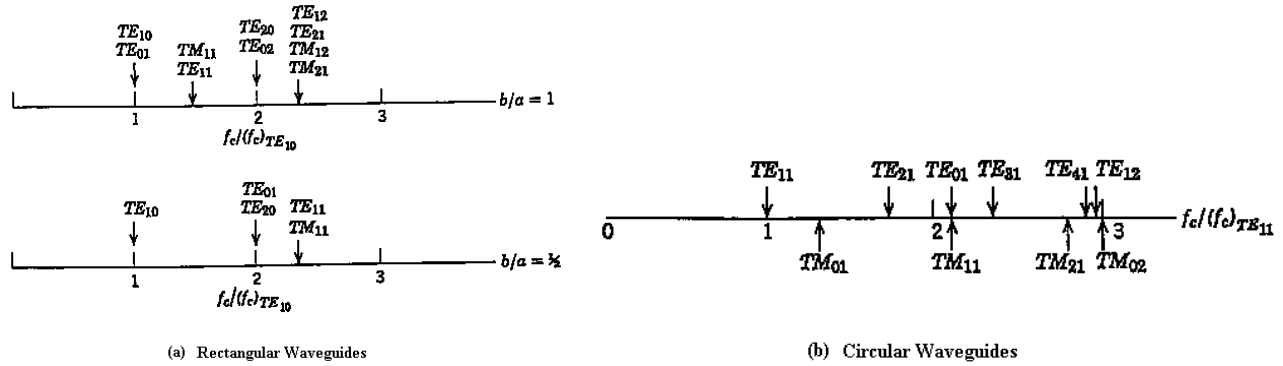
Figure 4. Relative Cutoff Frequencies of Higher Order Modes in Waveguides

processing, etc. It is obvious that the waveguide dimensions decrease as the selected mode to the primary waveguide so as to extract the second and all higher order modes, but not the primary mode, since its dimensions are such that the primary mode is below cutoff. Only the second mode is processed in the second mode magic tee since the third and higher order modes are extracted in the third mode magic tee prior to

processing, etc. It is obvious that the waveguide dimensions decrease as the selected mode number increases so that the procedure will be limited to only the first few modes to avoid network complexity. The actual modes to be selected depend on the usual rectangular waveguide dimensions (a and b) as illustrated in Fig. 4a while Fig. 4b shows a similar spectrum for circular waveguide modes to which the technique will be extended later. The initial
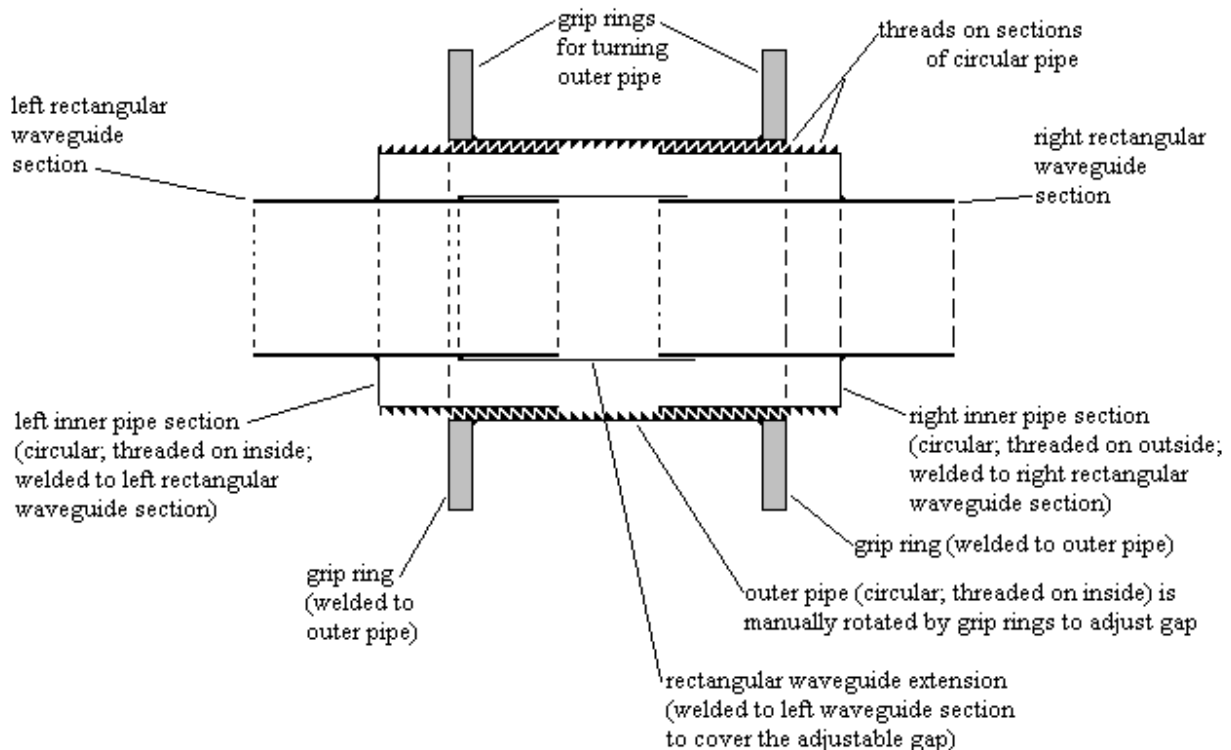

Figure 5. Schematic Diagram of Adjustable Length Rectangular Waveguide

design will therefore concentrate on the rectangular waveguide dimensions (a and b) of each magic tee such that all few modes of interest are excited within the available frequency band of the sweep oscillator.

One drawback of the proposed technique is the effect of the added junctions on the voltage standing wave ratio (VSWR) in the primary and branch waveguides of the multimode hybrid junctions [3]. Although slide screw tuners as well as rotary vane, ferrite or other types of phase shifters can be used to minimize the VSWR, an alternative method is proposed to avoid heating of tuning elements or power leakage from rotary vane slots, particularly in high power radar applications. This is shown schematically in Fig. 5 where the waveguide length is varied by a sliding mechanical technique which provides adequate phase shift. A threaded sleeve, which is turned using two outer rings attached to a circular pipe, introduces spacing between two adjacent waveguides which slide inside an outer waveguide provided for that purpose. This adjustable waveguide length method is novel and useful for testing the proposed hybrid junctions for each mode.

3. Experimental Procedure and Results

The three hybrid junctions were constructed and tested only for the fundamental TE_{10} as well the first higher TE_{20} modes only. The testing procedure employed a 2-18.6 GHz Hewlett Packard sweep oscillator whose output was displayed on a spectrum analyzer to determine the amplitude of each mode excited in the passband of the main feed waveguide. This output was then fed into the collinear arms of each hybrid junction and the signals at the sum and difference arms of each junction were then measured and compared with the expected values of the higher order mode. Slotted waveguides and two-way directional couplers were inserted in series with the collinear arms of each junction to measure the VSWR with and

without the adjustable length waveguide. The main test frequencies were 3, 6, 9 and 18 GHz, although secondary frequencies were employed as well. The maximum VSWR observed was 1.12 while the maximum deviation of the TE_{20} mode amplitude from the expected value was 7.6% for the rectangular magic tee, 9.1% for the hybrid rind and 6.9% for the directional coupler.

4. Conclusions

New hybrid junctions were designed, constructed and tested for the first two propagating modes in rectangular waveguides for standard laboratory measurements as well as radar applications. The design of the various waveguide sections will be optimized in the future using the method of moments [4] while the proposed variable-length waveguide proved helpful in the proposed hybrid junctions to minimize mismatch losses. The extension of multimode hybrid junctions to circular waveguides will be investigated separately once the rectangular waveguide multimode junctions are tested over several modes.

Acknowledgement

References

[1] H. Reich, P. Ordung, H. Krauss and J. Skalnik, "Microwave Theory and Techniques", Chapter 6, Van Nostrand, 1953.

[2] T. Ishii, "Microwave Engineering", second Edition, Harcourt Brace Jovanovich Publishers, Chapter 6, 1989.

[3] M. Skolnik, "Radar Systems", Chapter 4, McGraw-Hill, 2001.

[4] A. K. Hamid, I. R. Ciric and M. Hamid, "A Generalized Network Formulation for Symmetric Double-Step Waveguide Discontinuities", *Int'l Journal of Electronics*, Vol. 67, No. 3, pp. 427-435, Sept. 1989.

Michael Hamid Graduated from McGill University in Montreal with a B.Eng. degree in 1960, a M.Eng. degree in 1962 and from the University of Toronto with a Ph.D. degree in 1966, all in Electrical Engineering. He joined the University of Manitoba in 1965 where he became a Professor of Electrical Engineering and head of the Antenna Laboratory. He was a Visiting Professor at the Universities of California Davis and Central Florida and is presently a Professor of Electrical Engineering at the University of South Alabama. He is a past president of the International Microwave Power Institute, a Fellow of IEE and IEEE and published 307 referred articles and 25 patents.