in obtaining a 90 degree differential phase. If the "squeeze section" were uniformly deformed along a length, L, then the differential phase shift may be computed from:

$$dO = \left(\frac{2\pi L}{\lambda_{gb}} - \frac{2\pi L}{\lambda_{ga}}\right) \text{ radians}$$

Where λ_{gb} and λ_{ga} are the two guide wavelengths in the elliptic section.

For the tapered squeeze, the above is only an average approximation. The tapered squeeze is used not only to simplify the fabrication but also to minimize the slight impedance mismatch for the modes going through the squeeze section.

As the equal amplitude waves emerge from the "squeeze section" they will resume the normal guide velocity for the circular waveguide, BUT, will be shifted in phase by 90 degrees. The resulting combination of the two modes in the circular waveguide will be a circular polarized wave, as per our original requirements.

At this point you may be puzzled as to where the two orthogonal modes originated. They were NOT introduced by an ORTHO-MODE coupler as might be anticipated, but are generated directly at the "squeeze section" by orienting the elliptic cross section such that its major and minor axes are at 45 degrees to an incoming single TE11 mode, as shown by Figure 1C and 1D. The incoming mode in the circular waveguide, Figure 1C, is decomposed into two components oriented along the major and minor ellipse axes as shown by Figure 1D. The two voltage components will of course be lower in amplitude by 0.707, and in-phase with each other as they enter the squeeze section.

In consideration of the above discussion it will become evident that if the incoming mode were rotated in polarization by 90 degrees as shown by Figure 1C (lower drawing), one of the components will be reversed in orientation by 180 degrees from the situation in Figure 1C (upper drawing). The resulting circular polarized wave will then be reversed in rotational sense from Figure 1D (upper drawing).
And as per IEEE definition, Figure 1D (upper drawing) will result in CCW circular while Figure 1D (lower drawing) will result in CW circular polarization simply because the mode component oriented along the major axis of the ellipse will be advanced in phase by 45 electrical degrees while the component oriented along the minor axis will be retarded by 45 degrees from the original input mode. The total differential phase is 90 degrees.
Note however, that in Figure 1D (upper and lower drawings) the electric field along the minor axis has been reversed in direction by 180 degrees.

The simple recipe to determine the sense of circular polarization is to start at the field arrow head end of the advanced field component travelling away from you, then turn in the direction of the delayed component field arrow head. This process is illustrated by Figure 1D. The direction of turning (rotation) is the sense of the circularly polarized wave. This recipe may be used with any antenna situation provided reference directions of the fields are properly interpreted.

When this SQUEEZE SECTION differential phase shifter is combined with the ORTHO-MODE coupler, we have a complete circularly polarized converter with both senses of polarization available at the two isolated linearly polarized ports of the ORTHO-MODE coupler.

FABRICATION and ADJUSTMENT

From the above explanation it is evident how the "squeeze section" may be fabricated.
Using a short length, about 6 to 8 inches, of 3/4 inch Type-M copper water pipe, the ends should be plugged to a depth of about 1 inch with wooden dowels which fit snugly into the pipe, about 0.80 inch inside diameter. Two wooden block are now cut to have a very slight bulge in their centers, these are the squeezing blocks which are positioned diametrically opposite at the center of the pipe section and pressed together carefully in a vise or with C-clamps.
The extent of squeezing should not be more than about 1/16 inch decrease in pipe diameter, initially. If it is found that the squeezing is too great, the pipe may be brought back to near round by squeezing across a diameter that is at right angles to the initial squeeze. This may be done with simple flat blocks.

The exact amount of squeezing is best determined by direct measurement of the polarization circularity (elliptic ratio, maximum-to-minimum) of the converted circularly polarized wave.
To do this requires a source of r-f energy at the desired operating frequency, a transition into circular waveguide, and preferrably a circularly symmetric small horn such as the DUAL-MODE or modified DUAL-MODE horn. And in addition, a small linearly polarized horn which can be rotated axially to measure the elliptic ratio of the radiated signal on axis, i.e., the axial ratio.
Separate the antennas by at least 15 inches (at X-band) to be sure of negligible interraction between antennas. The measurement area may be a closed room provided that the walls are not metallic or that there are no large flat reflecting surfaces in the immediate area.

A word of caution about r-f radiation and possible health effects. While an acceptable level of constant r-f radiation is about 1 milliwatt per square centimeter, it is advisable to NEVER look into waveguides or small antennas that are radiating even low power, at close range. Since radiation dilutes (attenuates) as the square of the distance, the level of radiation 10 wavelengths (about 10 inches at X-band) from a small antenna, such as the dual-mode horn, will be only about 10 times weaker on axis than the power level at the input to the horn. The IMU dual-mode small aperture antenna has an on-axis gain of close to 10.

The fine tuning process for the polarizer then is to measure the maximum to minimum signal level radiated on axis of the horn by rotating the measurement probe antenna completely through 360 degrees of orientation. Two adjustments constitute fine tuning. First squeeze very slightly until the best circularity is achieved, then rotate the "squeeze section" from its initial 45 degree orientation by small amounts. Repeat circularity measurements with each adjustment of squeeze and orientation. The process is continued until the circularity is less than about 0.5 dB. While further refinement can be done, it is questionable as to the significance of the circularity measurement in any particular environment.

At a circularity (axial ratio) of 0.5 dB the ratio of power in the desired sense circular polarization to the opposite sense (cross polarized) power is 30.8 dB.
At an axial ratio of 1 db the ratio of circular polarized levels of opposite sense is 24.8 dB.

For those interested, a general equation for the ratio of power in the two senses of circular polarization for a given axial ratio is:

$$\frac{P_{\text{desired sense}}}{P_{\text{opposite sense}}} \text{ (in dB)} = 20 \text{ LOG} \left(\frac{AR + 1}{AR - 1} \right)$$

Where AR is the axial elliptic ratio (axial meaning on axis) as a number greater than 1.
If the axial ratio is measured in decibels, then the value of AR (a pure number ratio) is:

$$AR = \text{ANTILOG} \left(\frac{dB}{20} \right)$$

ADDITIONAL NOTES

In some circumstances a relatively long feed line (waveguide) may be required between the circular polarization converter and the actual radiating antenna. While copper water pipe is a good low loss waveguide, it has one major problem. It is that the pipe is not available as precision circular tubing, but is slightly elliptic. If used as a straight waveguide feedline, the resulting out-of-round cross section can result in an indeterminate amount of differential phase shift and consequently any manner of elliptic polarization at the output end for a pure linearly polarized wave at the input.

Fortunately this apparent deficiancy in circular tolerance of the pipe may be used to advantage and put to practical use if circular polarization is contemplated in an antenna system.

For a relatively long section of copper pipe waveguide, the amount of differential phase shift may exceed 90 degrees by a large amount. This will be of little concern for narrow band, or single frequency operation. The total differential phase shift may actually be adjusted to (90 + N*180) degrees, where N is an integer.

In a practical situation, the pipe circular waveguide may be both rotated and slightly squeezed any where along its length to achieve the desired circular polarization elliptic ratio by direct measurement. Once the proper rotational orientation and incremental squeeze have been established, the input exciting waveguide (ORTHO-MODE coupler for both sense circular or simple rectangular to round transition for single sense circular) should be locked together. The long feedline effectively replaces the "squeeze section" differential phase shifter described earlier in this report.

The true sense of circular polarization with the long feedline/polarizer is difficult to determine using the simple recipe given earlier. The easiest way to determine sense here is by direct measurement with a known circularly polarized antenna probe. This may be a dual-mode antenna fed with a "true" 90 degrees differential phase shift polarizer, or more simple by means of simple helical antennas where the polarization sense is merely the screw (twist) direction of the helix.

The combination feedline/phase shifter can be used to advantage in Cassegrainian reflector feed systems.