

MIMICAD TECHNICAL REPORT NO. 16

Software Validation Project

by

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Software Verification Effort at the MIMICAD Center For Microstrip Passive Components

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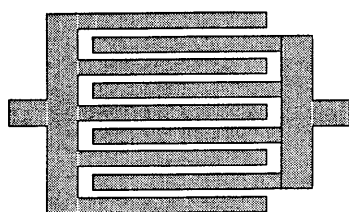
I. Introduction

Accurate simulation capabilities are vital in achieving first-pass designs. In an effort to enhance current MMIC design processes, the Center for Microwave/Millimeter-Wave Computer-Aided Design (MIMICAD) at the University of Colorado, Boulder, has been actively involved in the development of simulation programs for monolithic microwave integrated circuits. Full-wave simulation programs for modeling passive single-layer and two-layer microstrip components, coplanar waveguide and coplanar stripline structures, and 3D packaging effects have been developed. Most of these programs are developed using a rigorous formulation based on a mixed-potential integral equation approach in conjunction with the method of moments. Thus, in principle, they can yield accurate results.

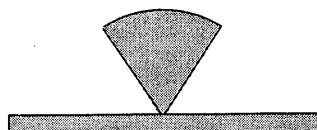
Motivated by the need to verify the accuracy of the simulation programs, a software verification effort was initiated by the MIMICAD Center, Boeing, and the National Institute of Standards and Technology (NIST). While the main goal of this effort was to conduct carefully-calibrated measurements to validate the accuracy of the Center's software, the secondary objective was to examine measurement consistency between the participants. The verification effort was partitioned into different phases for testing different MMIC configurations. This verification project was focused on single-layer microstrip structures on GaAs substrates with no vertical interconnects. Inputs on test structures were solicited from all MIMICAD sponsors. Twelve structures, as displayed in Figure 1, were selected for testing and fabrication. This report summarizes the results of the first phase of the software verification effort on these twelve structures.

II. Test Procedure

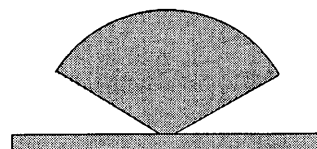
The twelve test structures selected were all two-port microstrip components commonly used in MMIC designs. Mask layout as well as fabrication of the test structures was done at Boeing. Details of the wafer fabrication can be found in [1]. To assess measurement consistency, two wafers of the same test structures were fabricated for round robin measurements among the MIMICAD sponsors. Initial measurements on the test structures were done by Boeing and NIST. Subsequent measurements were later done by Texas Instruments and TRW. To minimize de-embedding errors, a set of on-wafer TRL calibrations as well as measurements of the complex characteristic impedance of the line was performed by NIST. The S-parameters measured by each participant were then transformed to a real impedance of 50 Ω using the de-embedding software provided by NIST.



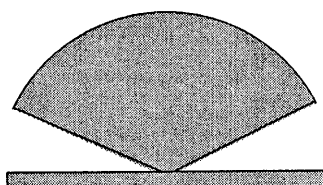
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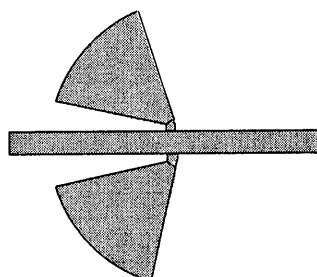
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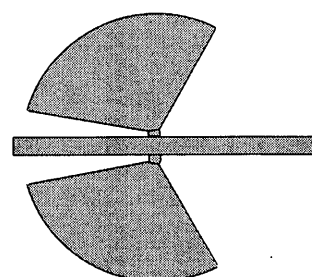
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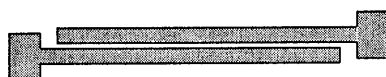
4: 120° Radial Stub
Label: `r_stub4`



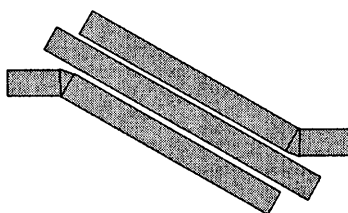
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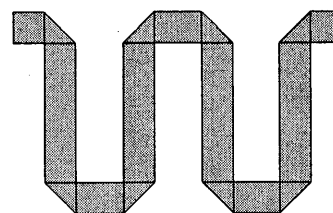
6: 120° Radial Stubs
Label: `match2`



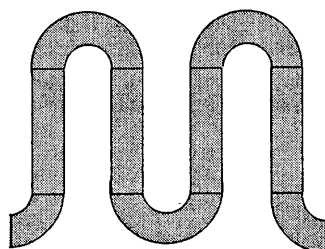
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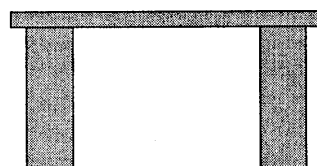
8: BandPass Filter
Label: `filter2`



9: 90° Microstrip Bends
Label: `bends`



10: Microstrip Bends
Label: `meander`



11: Shunt Stubs
Label: `sh_stubs`



12: Series Stubs
Label: `ser_stub`

Figure 1: Geometries of the test structures.

At the MIMICAD Center, all twelve structures were simulated over the frequency range of 10 to 40 GHz using one of the Center's software programs, PMESH [2,3], for single-layer microstrips. One of the unique features of PMESH not found in many other full-wave simulators is its versatility. Because it can use both rectangular and triangular cells of irregular sizes to model a structure, the program can simulate most kinds of microstrip circuit components including the radial stubs shown in Figure 1.

Prior to each simulation, the test structure was discretized into combinations of rectangular and triangular cells using either AUTOGRID or MBUILD [4,5]. AUTOGRID and MBUILD are two graphical tools developed by the Center to interface to their various simulation programs. While AUTOGRID can import foreign files such as GDSII and EGS files created by commercially-available layout tools, MBUILD is a stand-alone interface for constructing the test structures using pre-gridded blocks. A set of EGS files containing the dimensions and geometries of the test structures were provided by Boeing. With these files, the gridding of the test structures was made simple using AUTOGRID. In the testing process, most of the structures were gridded using AUTOGRID. However, some of them were reconstructed using MBUILD to examine the effect of grid/cell variation. For all cases, a gridding guideline of $\lambda_g/20$, where λ_g is the guided wavelength, for the cell size was used. This cell size was empirically determined to be the optimal cell size for simulating microstrip lines [6].

III. Test Results

The results of the comparison for all twelve structures can be found in the Appendix. For each structure, we included the gridded geometry and plots of the S-parameter in magnitude and phase. Each plot contains the simulated data as well as the measured data from the various sponsors.

The results show that the measurements performed by the various sponsors were in general consistent with one another. Isolated discrepancies such as the NIST measurements on the capacitor and the series stubs and the TRW phase measurements did exist. Upon a closer examination, it was discovered that the NIST measurements on the capacitor and series stubs were in fact very similar to the response of the dc block. This inconsistency was most likely caused by a simple file error. The discrepancy in the TRW measurements occurred in the phase of S_{11} only. Therefore, this disagreement was most likely caused by an error in the specification of the reference-calibration plane.

The simulated results in general compared well with the measured data. However, for some types of structures, the results were found to be sensitive to the discretization, particularly when triangular cells were used to approximate a smooth continuous surface. For example:

- A small frequency shift can be observed in the responses for the radial stub structures. Numerical experimentation showed that this shift was partly due to the use of triangular cells in discretizing the radial stub region. Figure 2 shows two different gridding schemes used to model the radial stub labelled r_stub2. Figure 2(a) shows the original stub gridded using AUTOGRID while Figure 2(b) shows the stub reconstructed from MBUILD using mostly rectangular cells. The result of the comparison can be seen in Figure 3 which shows the magnitude of S_{12} for the simulated as well as measured data.

As can be seen, for the rectangular-cell gridding scheme, the frequency shift between the measured and computed data was not as pronounced as the triangular-cell gridding scheme. Another factor which could also contribute to the frequency shift between the measured and computed values was the approximation of the arc boundary of the radial stub with piece-wise linear segments. When the smooth arc is segmented into linear straight lines, the effective dimension of the radial stub is no longer the same as the original structure. This in turn can cause a frequency shift in the response curves.

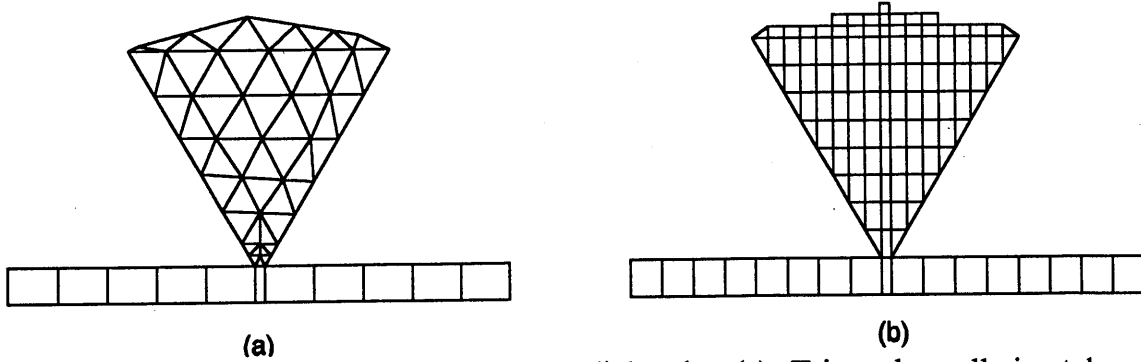


Figure 2: Different gridding scheme for the radial stub. (a) Triangular cells in stub region. (b) Rectangular cells in stub region.

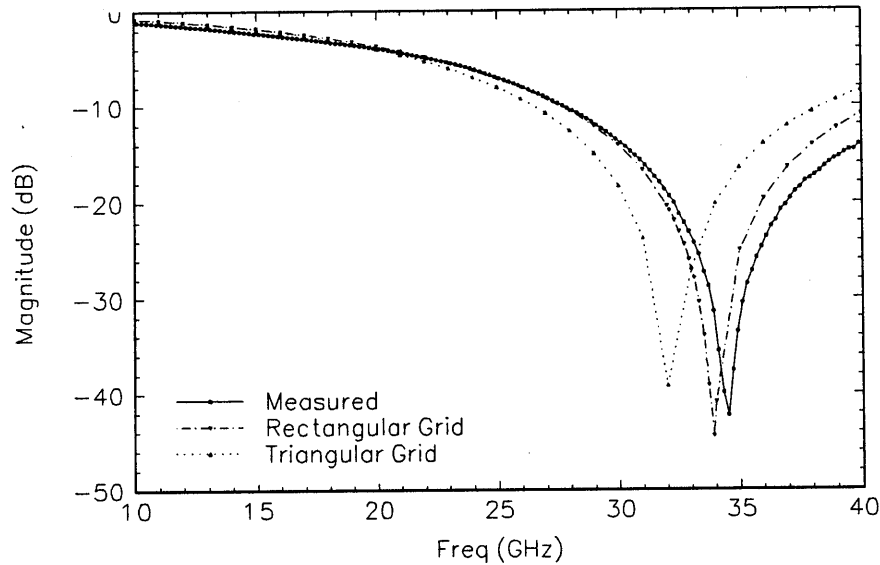


Figure 3: Measured and simulated S_{12} for r_stub2 .

- Structures containing small gaps, such as the filter and the dc block structures, must be gridded along the transverse as well as the longitudinal direction in order to account for the coupling fully. The good agreement shown for the filter structure was obtained after the structure was re-gridded along the transverse direction. With a one-cell-per-width original gridding scheme, the results showed a slight frequency shift and a lower S_{12} magnitude in the simulated responses across the frequency band.

- For structures containing rounded-corner bends such as the meander line structure, the arc regions must be modeled properly, particularly when the structure contains many of these corners. Numerical experimentation revealed that when the arc regions were gridded using all triangular cells, artificial rippling effect could occur in the simulation results. The cause of this rippling effect was not so much due to the use of triangular cells but more to the random segmentation of a smooth curve into piece-wise linear segments. As shown in Figure 4(a), when an arc is discretized into finite number of nodes, the equivalent line-width along the piece-wise linear corner is no longer uniform. This can introduce small reflections along the line. When the number of arcs increases for a given meander line, these reflections can accumulate and produce an artificial rippling effect in the simulated results. This phenomenon was observed with the rounded-corner meander line shown in structure 10 of Figure 1. To eliminate this discretization effect, the optimal gridding scheme would be to approximate the arch using rotated rectangular cells combined with triangular cells as shown in Figure 4(b). By making the width of the rectangles the same as the line width, a uniform width along the arch is ensured. However, this type of gridding generally cannot be achieved in AUTOGGRID since the arcs are already segmentized by the time it is read into AUTOGGRID. To obtain the gridding shown in Figure 4(b), the user will need to reconstruct the structure using a tool such as MBUILD to recapture the arch. For structures containing a few isolated rounded-corners, the rippling effect due to the random segmentation is negligible. However, for structures containing multiple rounded-corners in series, care must be taken in discretizing the corners.

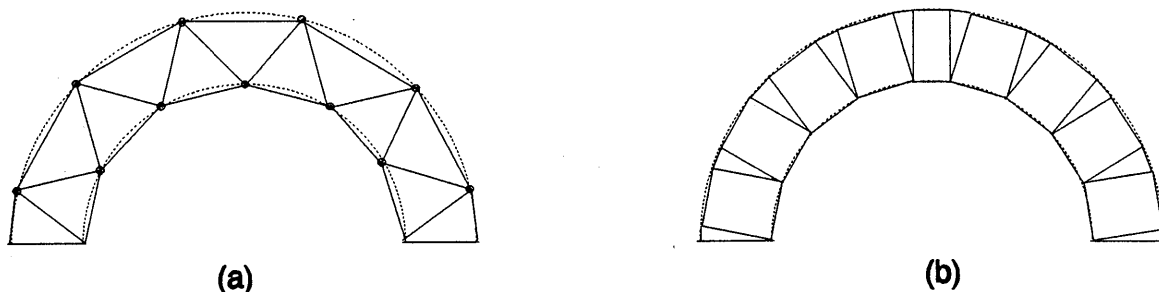


Figure 4: Segmentation of an arch. (a) Triangular cells. (b) Combinations of rectangular and triangular cells.

In comparing the simulated data with the measured values, another factor which could affect the results was the difference in the reference impedance used for the S-parameters. As mentioned previously, the measured S-parameters were normalized to a real $50\ \Omega$ reference impedance. In contrast, the S-parameters computed by PMESH were defined with respect to the intrinsic (complex) characteristic impedance of the line. This difference in the normalizing impedance can contribute some amount of discrepancies. However, because the characteristic impedance of the line for our structures was very close to $50\ \Omega$, the effect of this impedance disparity was negligible.

IV. Conclusion

The first phase of the software verification project has been completed successfully. This effort demonstrated the versatility as well as the accuracy of PMESH. It also brought forth new refinements on PMESH and new understanding of the discretization effect. Although a full-wave simulator like PMESH is capable of yielding accurate results, the solution can depend on the gridding, particularly for complex geometries. Because it is difficult to automate the gridding process for PMESH, the responsibility of proper gridding currently lies with the user. The best guideline for gridding is to follow physical intuitions and make the grid conform to the proper current flow as much as possible.

Verification of software is a non-ending task. It is only through continuous testing that we can make the program robust. The participation of the industry sponsors provided a unique opportunity for us to carry out the software verification effort. Although this project has been completed, we hope to continue this effort by examining other types of MMIC structures and configurations.

V. Acknowledgements

The MIMICAD Center would like to acknowledge Dr. K. C. Gupta, Dr. Ray Shimoda of Boeing, and Dr. Dylan Williams of NIST for leading the software verification effort. The Center would also like to thank all the sponsors, particularly TI and TRW, for participating in this effort. The authors would like to acknowledge Ms. Janet Anstett for providing assistance in the simulation process.

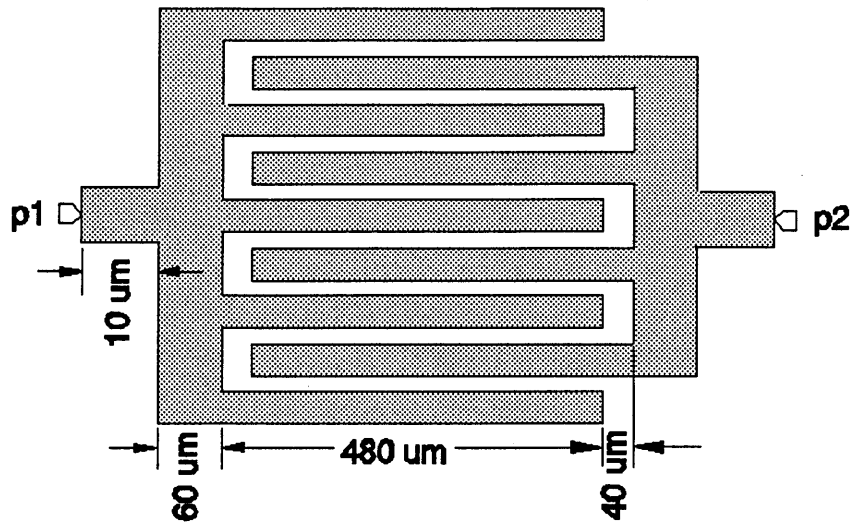
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- [1] R. J. Furlow, R. Shimoda, D. F. Williams, R. B. Marks, and K. C. Gupta, "Benchmark for CAD software," *38th Proceedings of ARFTG*, pp. 97-106, 1991.
- [2] D. C. Chang and J. X. Zheng, "Electromagnetic modeling of passive circuit elements in MMIC," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1741-1747, 1992.
- [3] D. C. Chang, D. I. Wu, and J. X. Zheng, "Numerical modeling of passive networks and components in monolithic microwave integrated circuits," *Directions in Electromagnetic Wave Modeling*. (Ed. Felsen and Bertoni), pp. 249-263. New York: Plenum Publishing, Spring 1992.
- [4] *MBUILD User's Guide*, the MIMICAD Center, University of Colorado, Boulder, 1992.
- [5] *AUTOGRID User's Guide*, the MIMICAD Center, University of Colorado, Boulder, 1992.
- [6] D. I. Wu, D. C. Chang, and B. L. Brim, "Accurate numerical modeling of microstrip junctions and discontinuities," *Inter. J. of Microwave and Millimeter-Wave Computer-Aided Engineering*, vol. 1, pp. 48-58, Jan. 1991.

APPENDIX

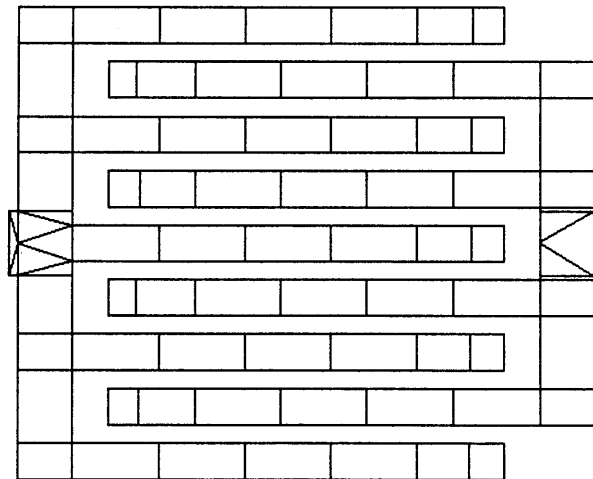
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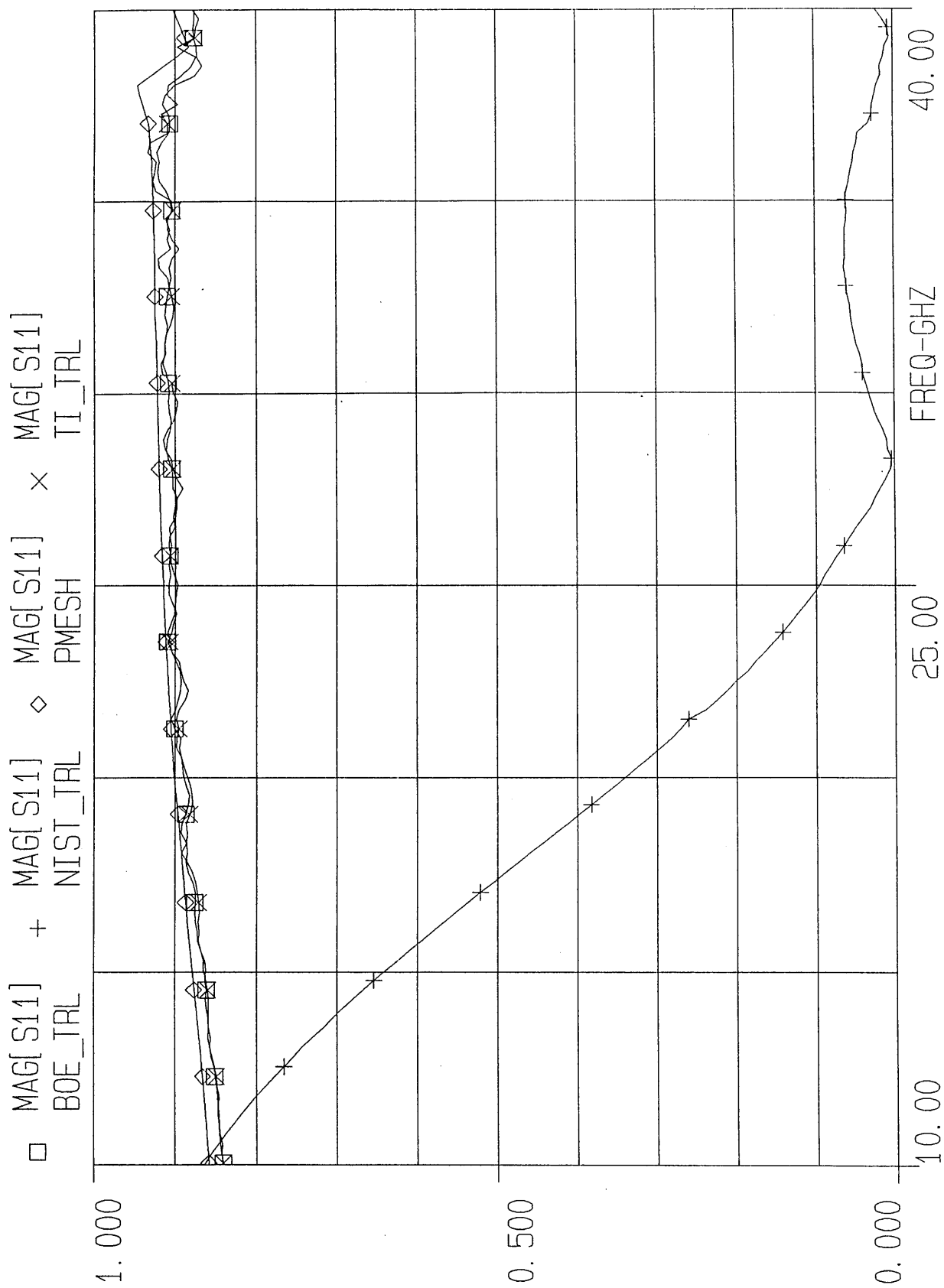


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Finger width: 40 um
Feed line width: 73 um

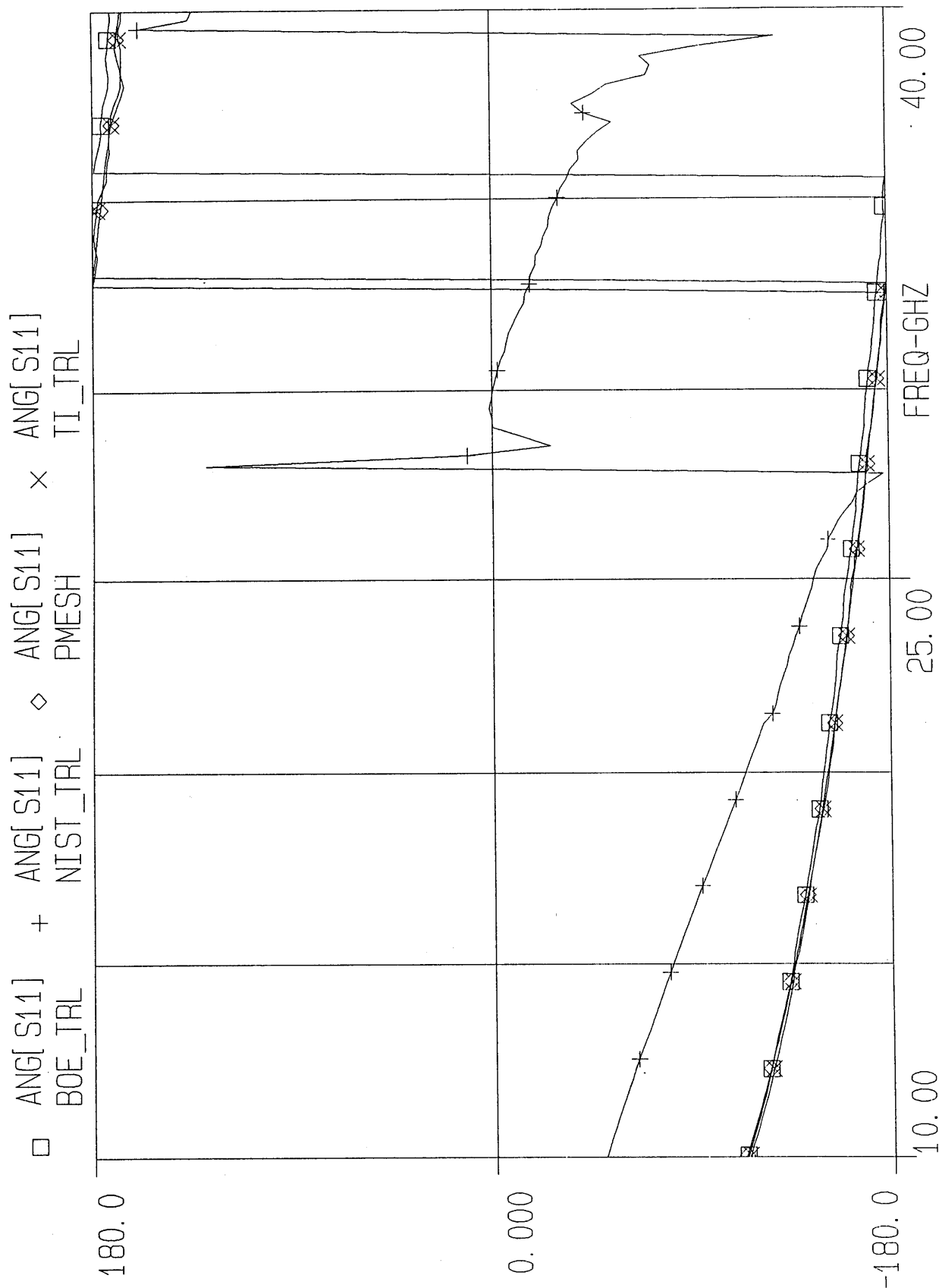
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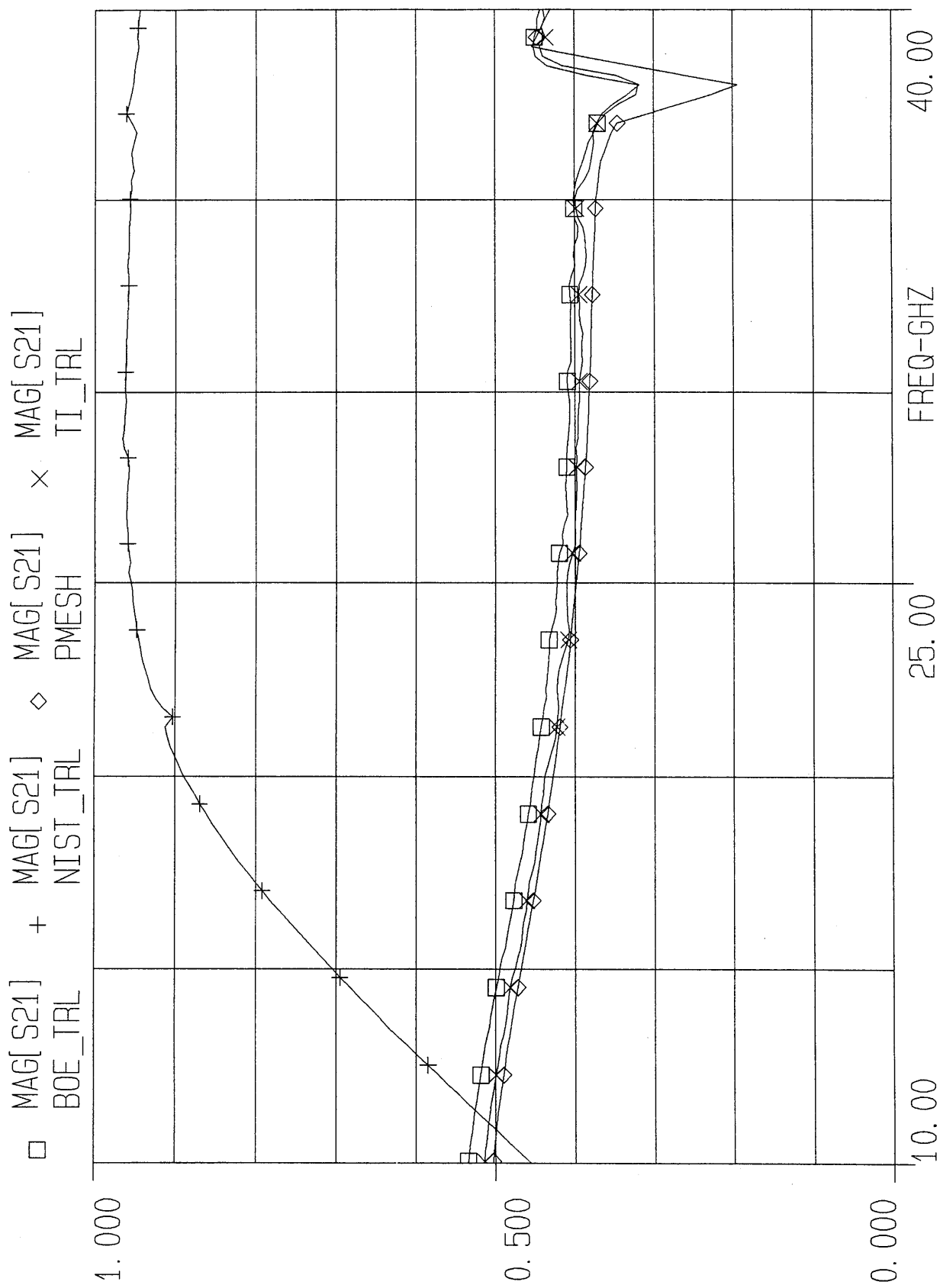
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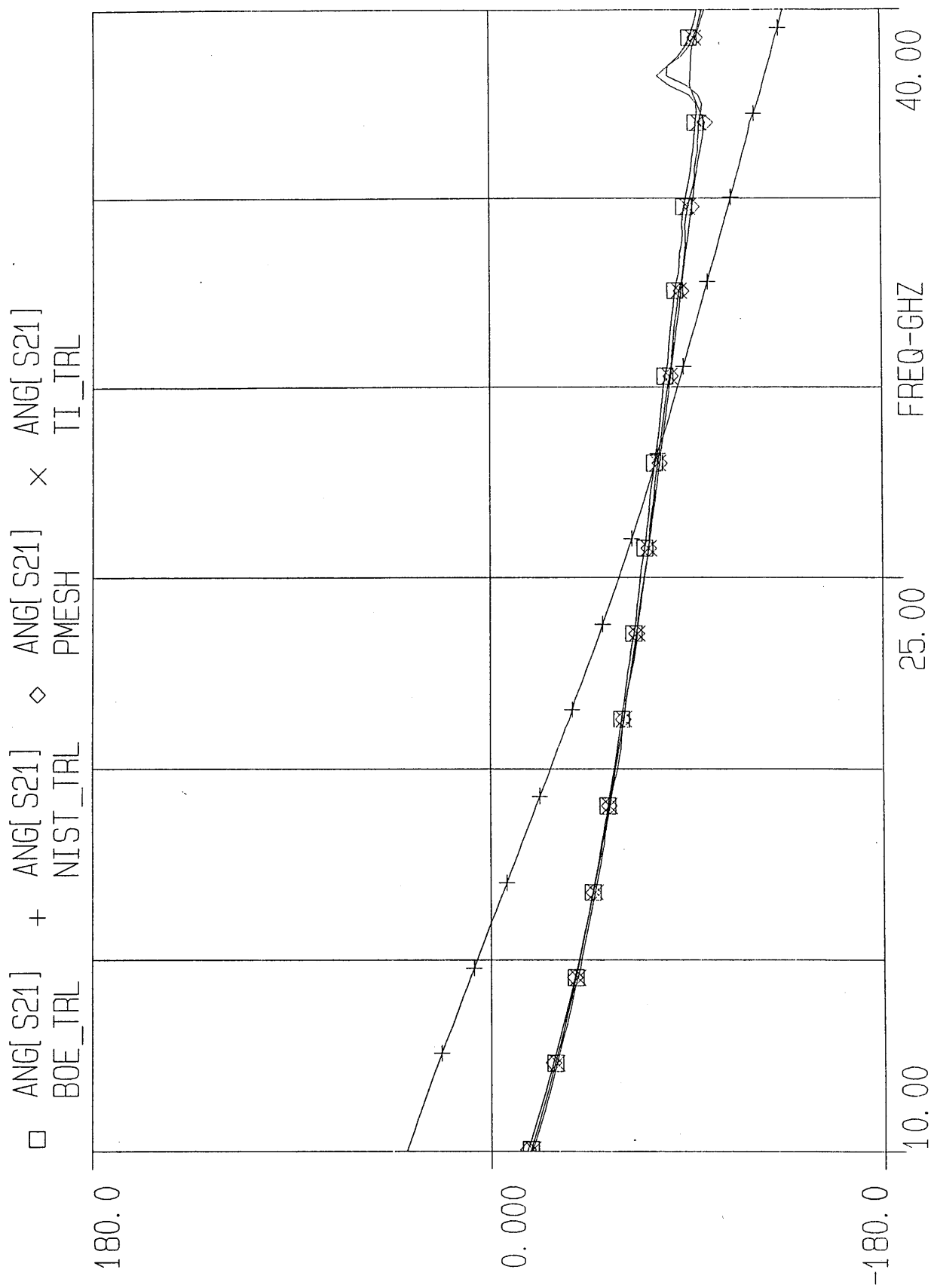
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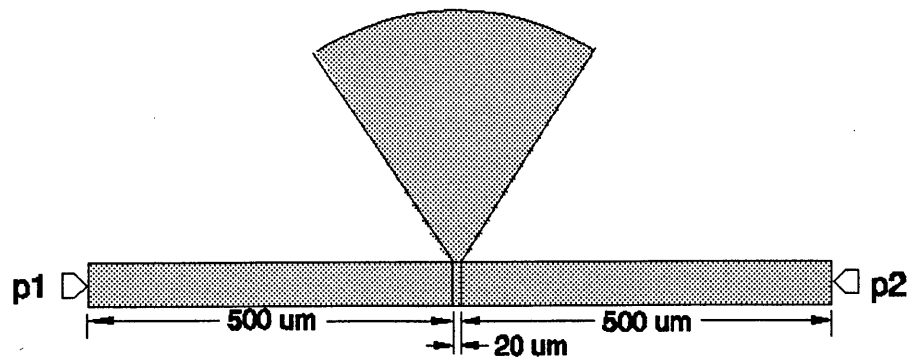


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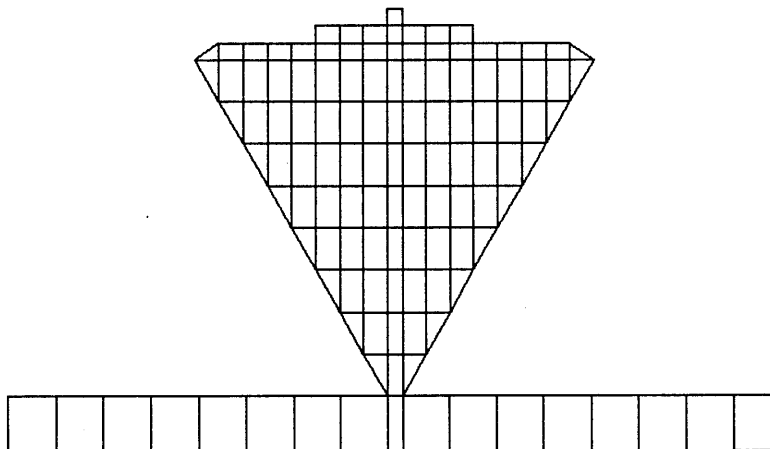
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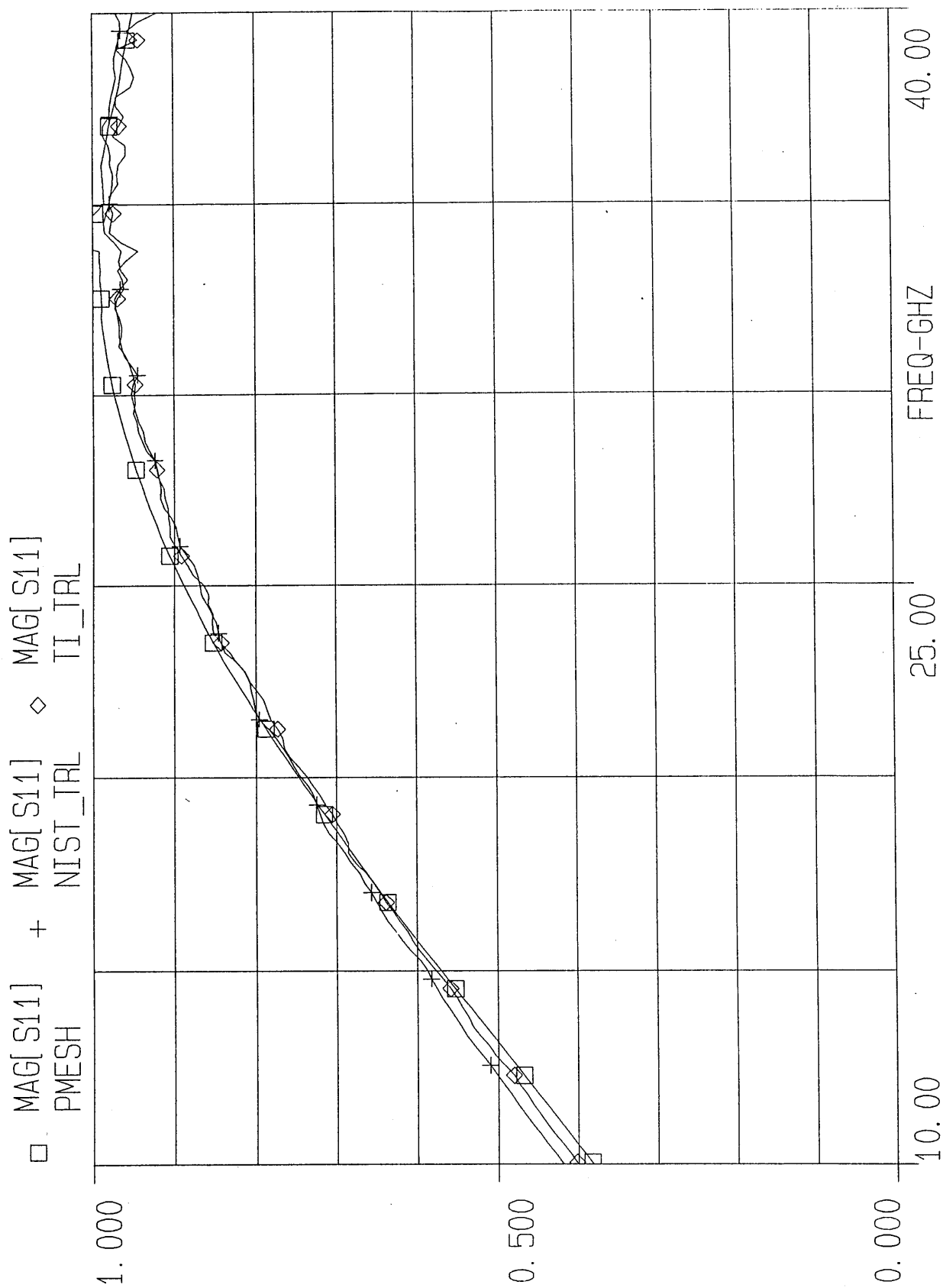


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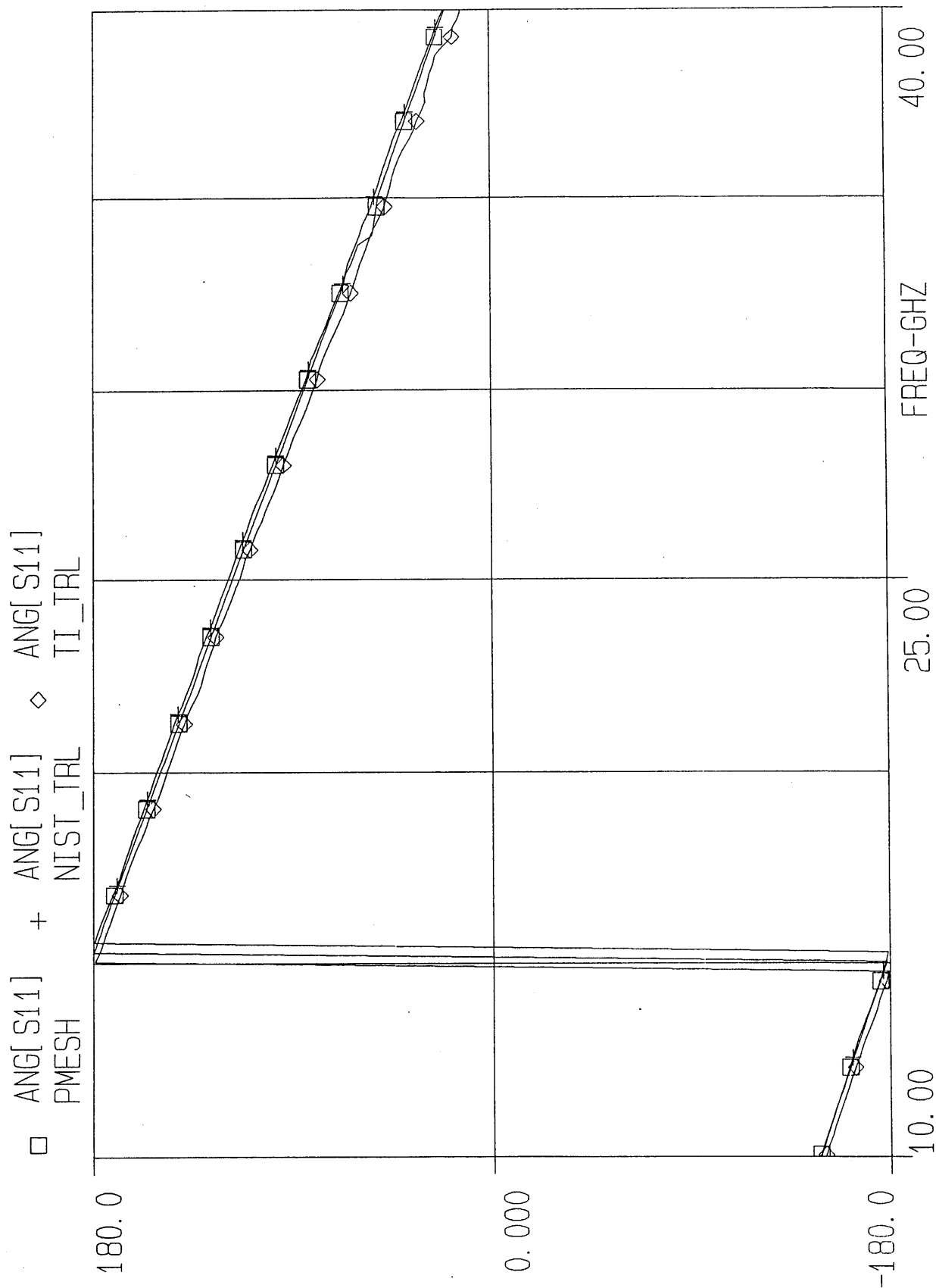
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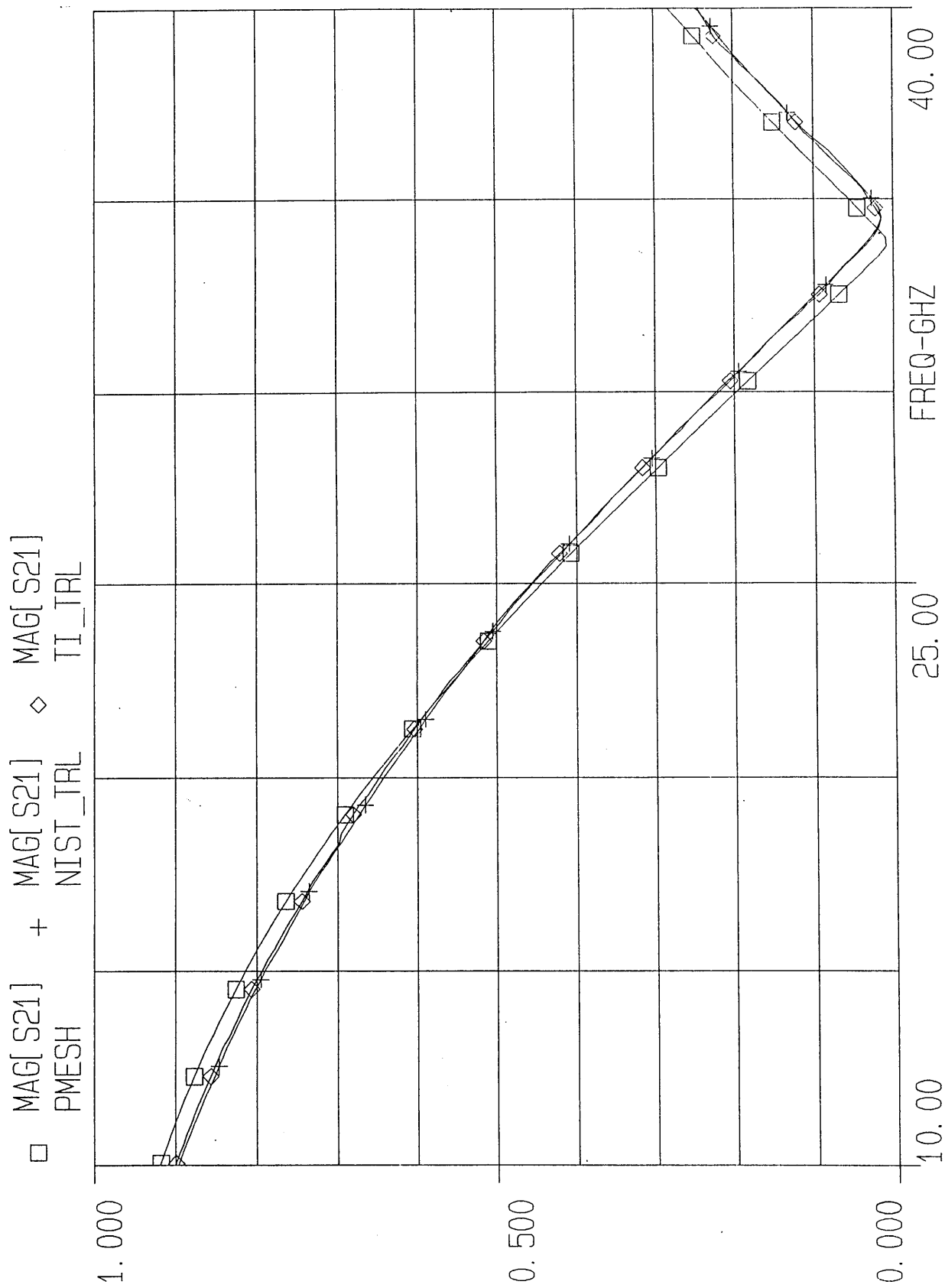
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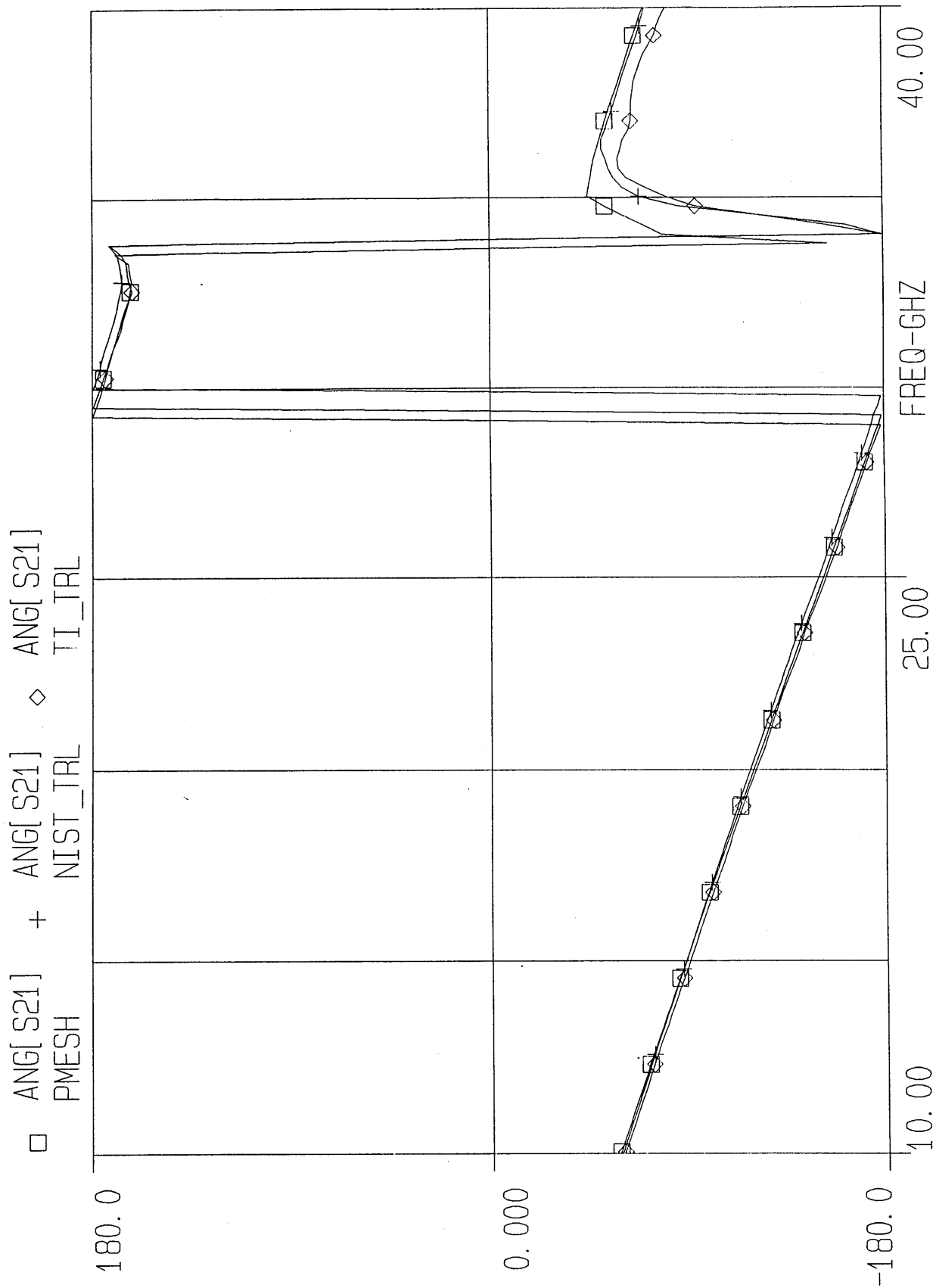
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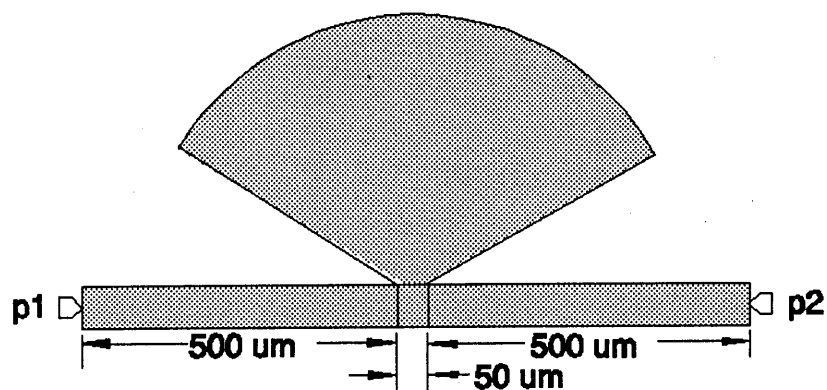
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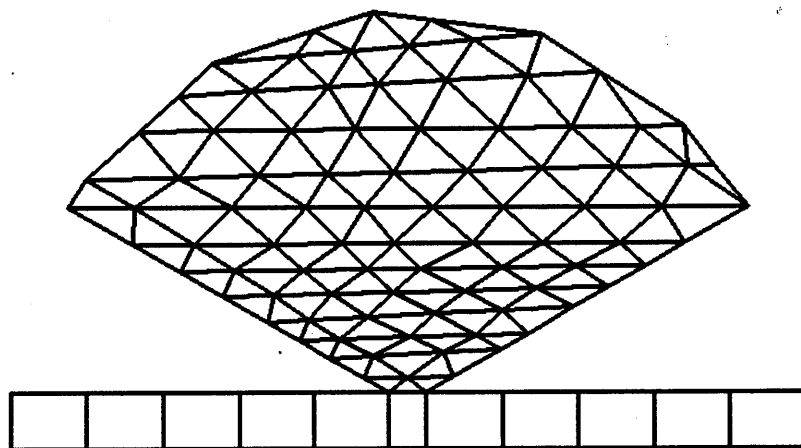


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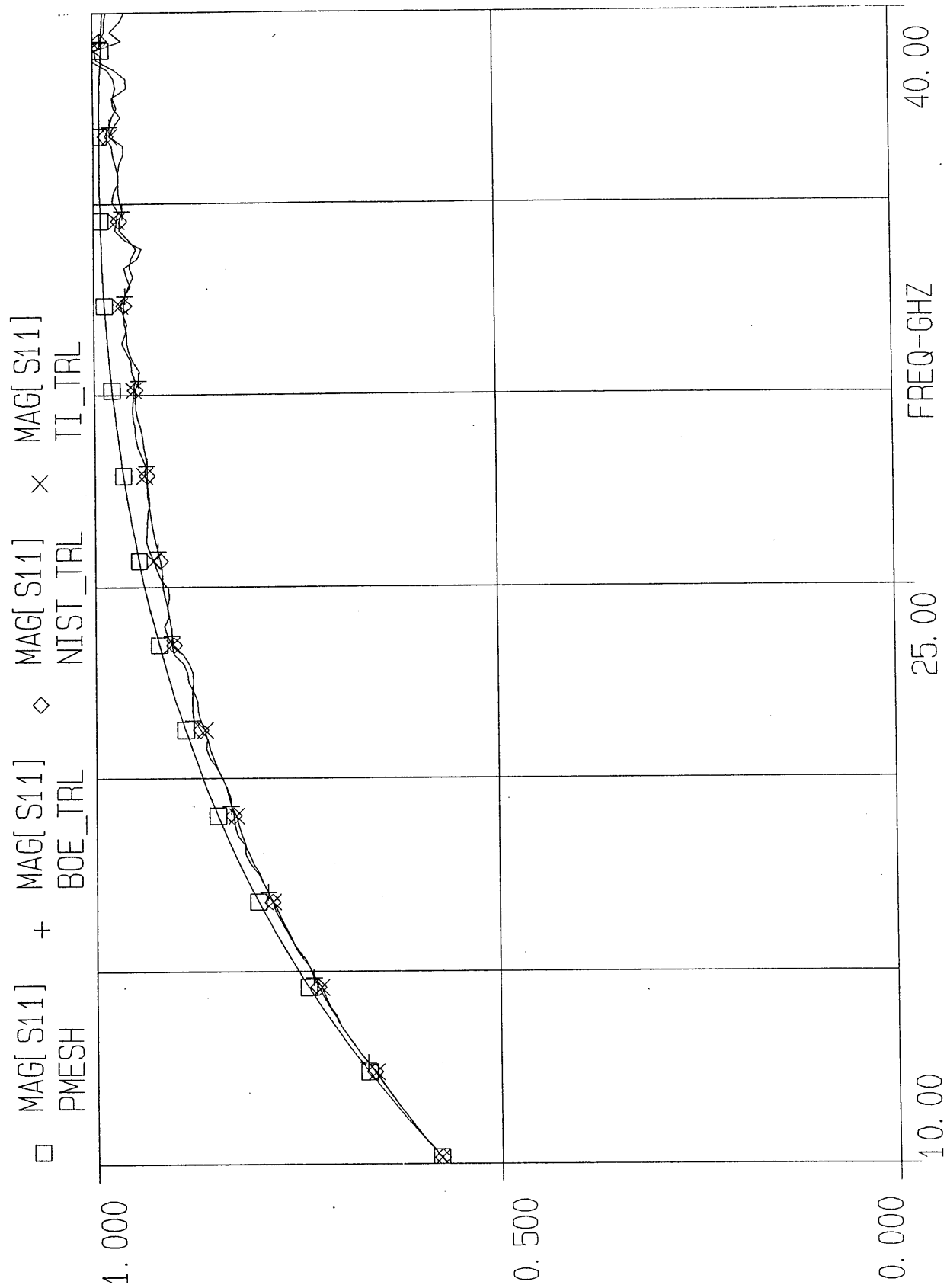


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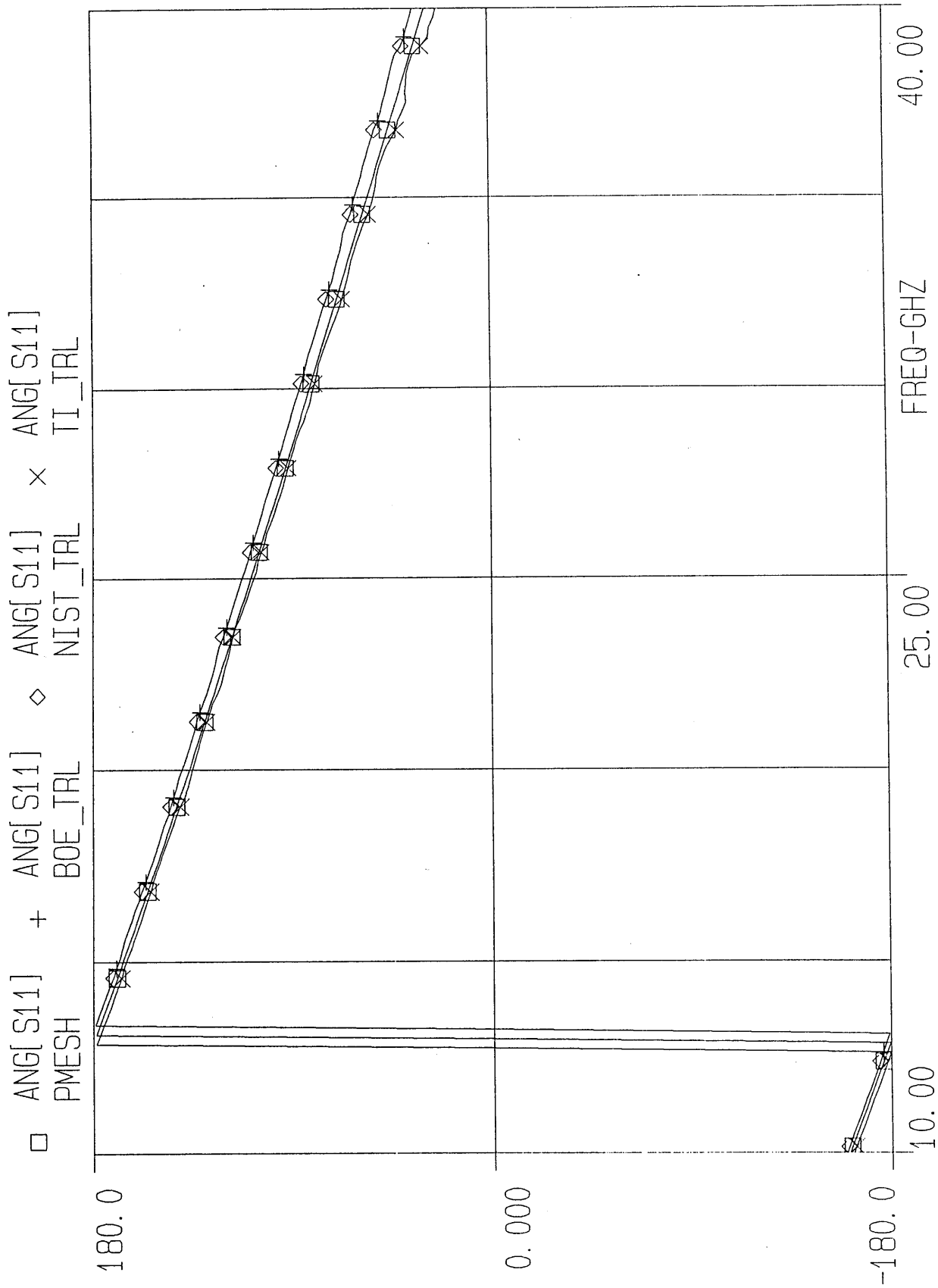
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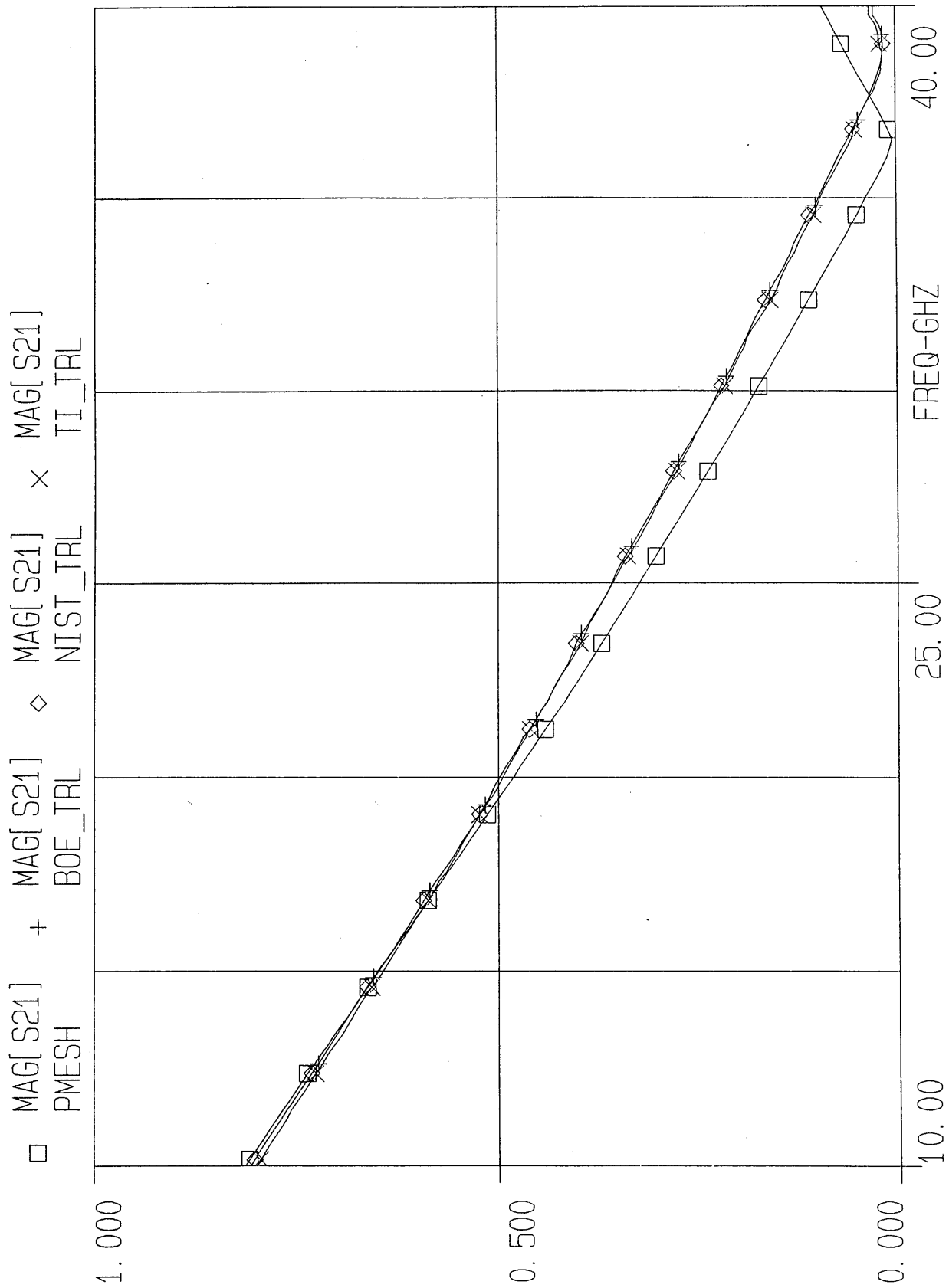
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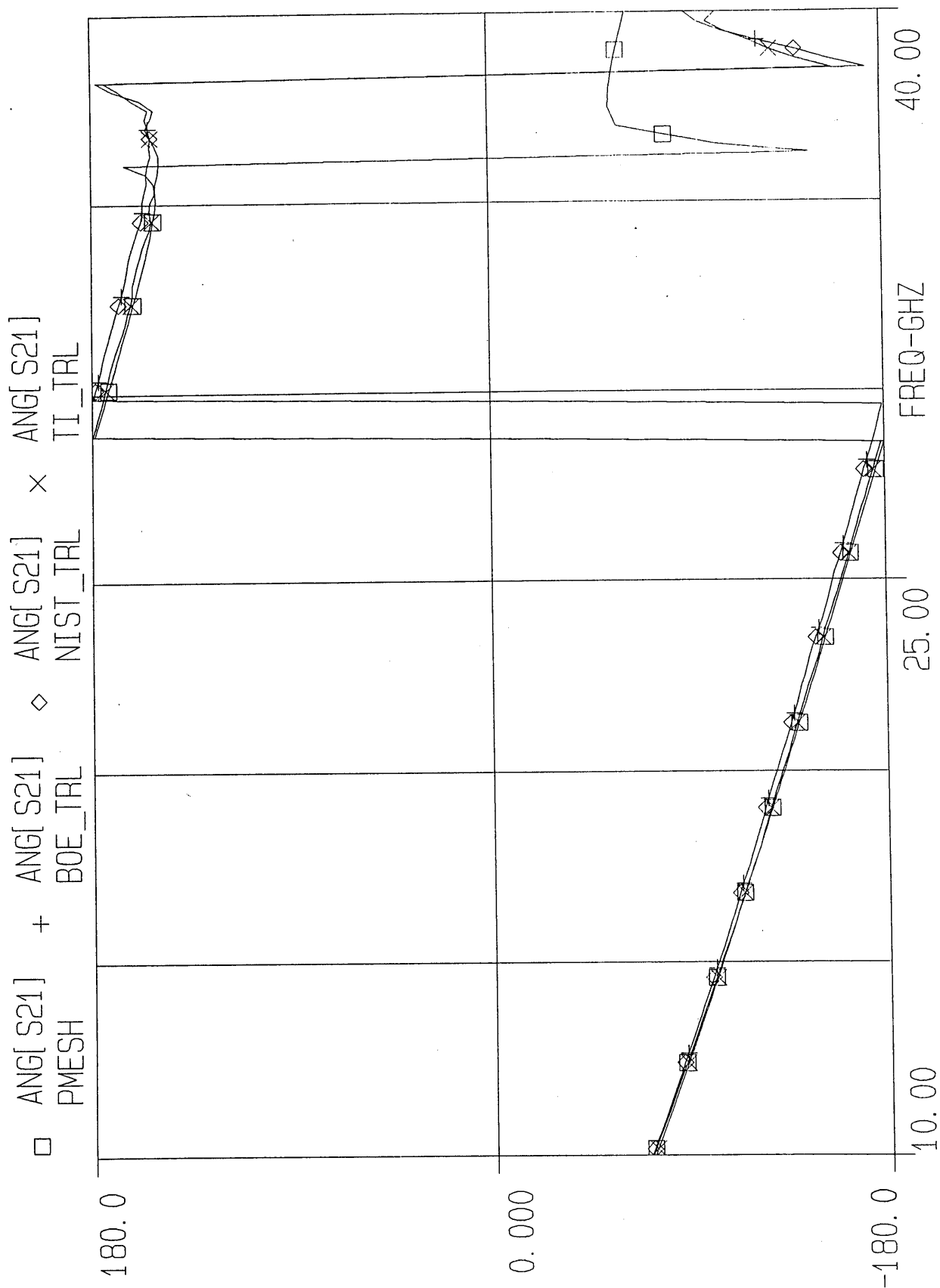
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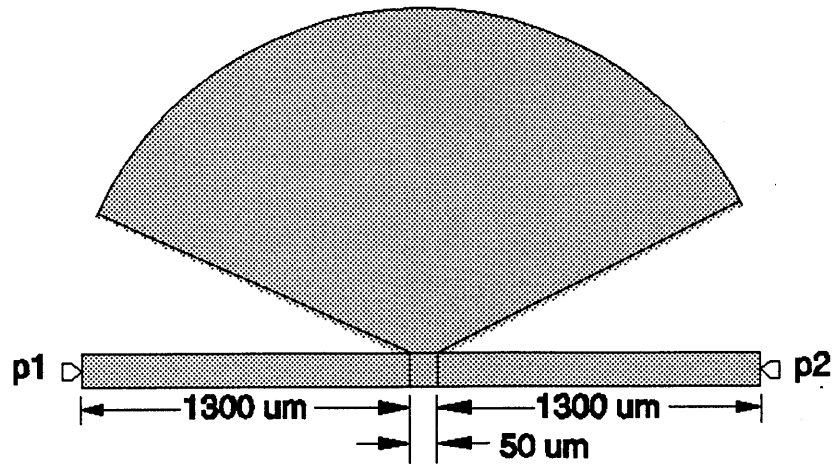


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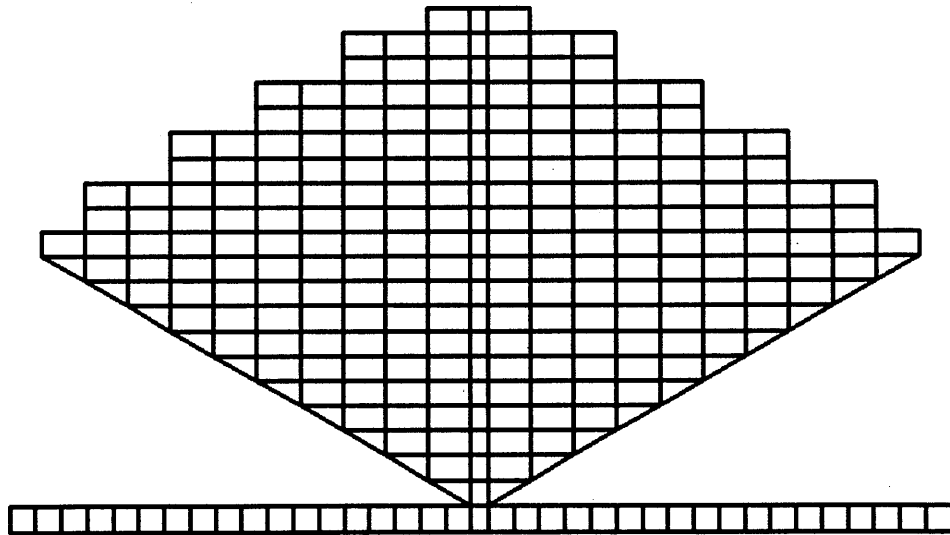
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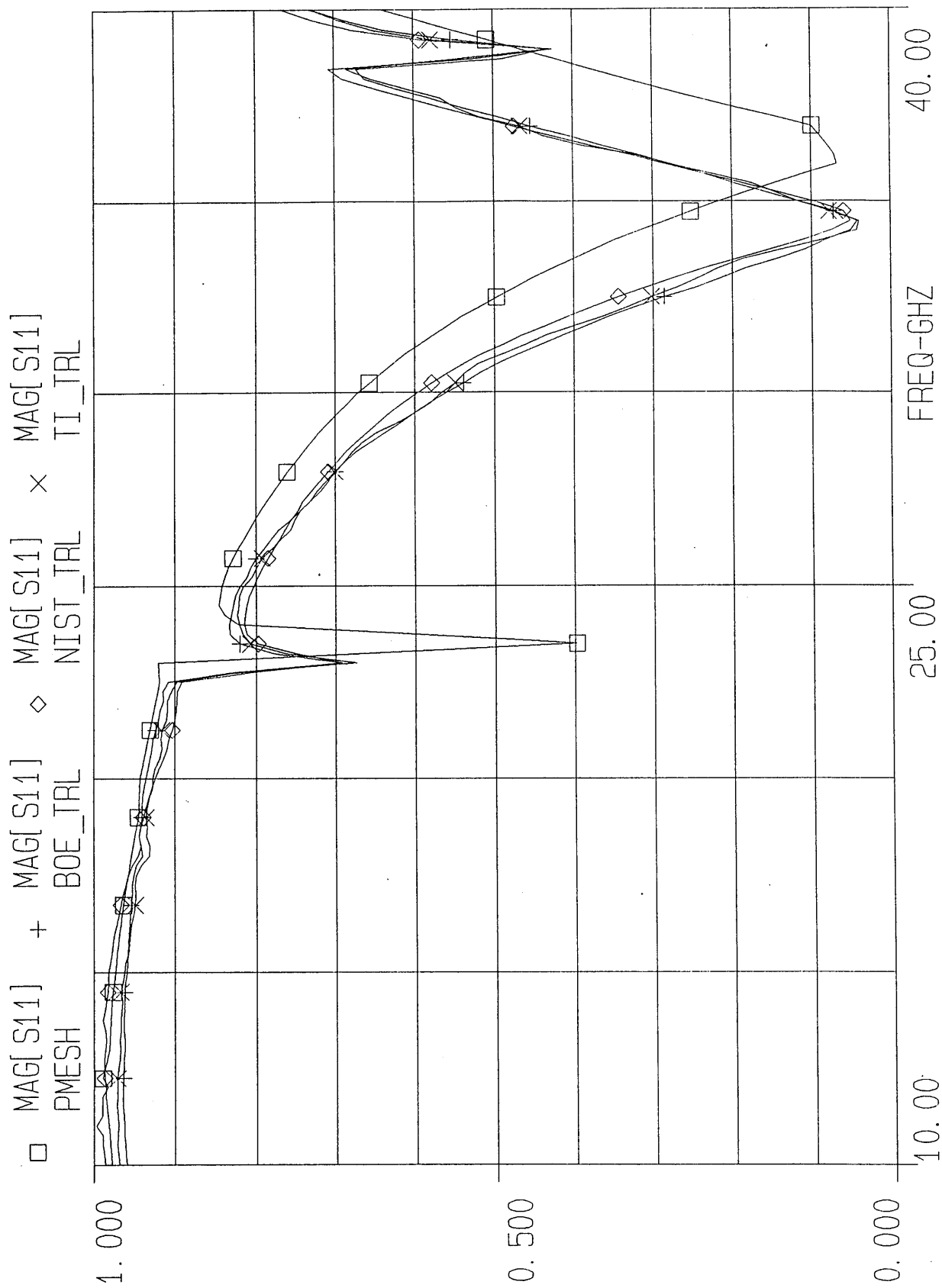


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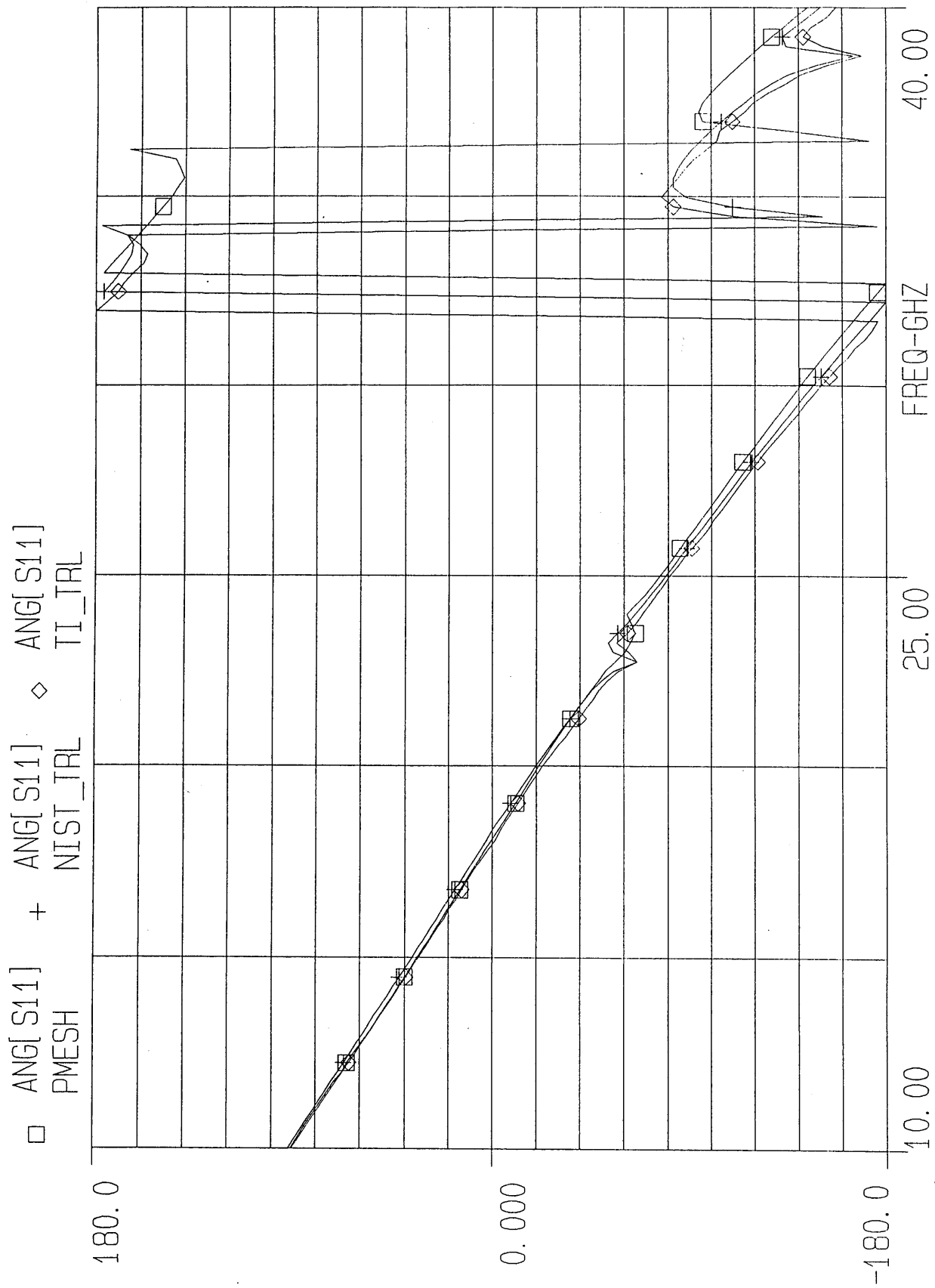
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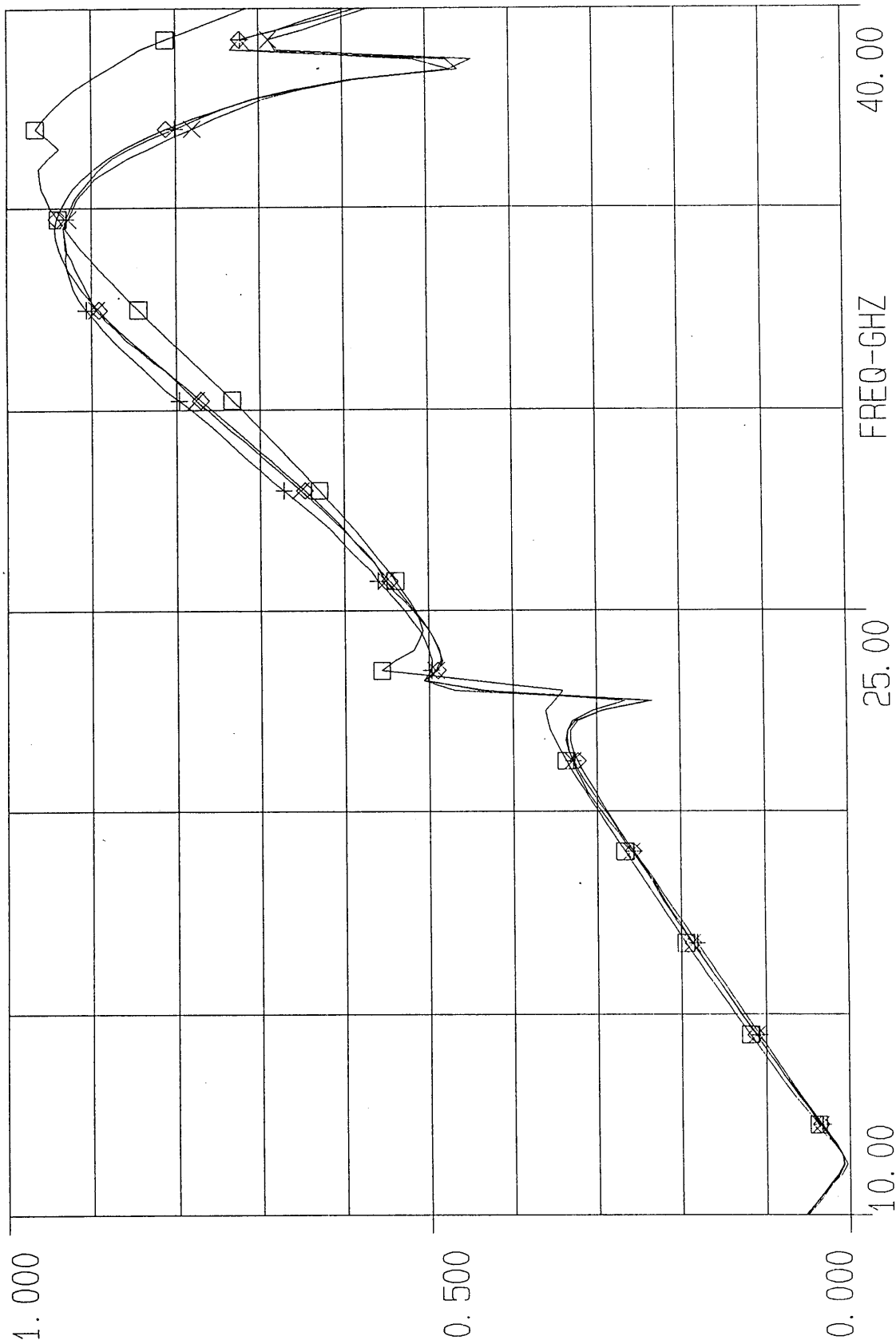


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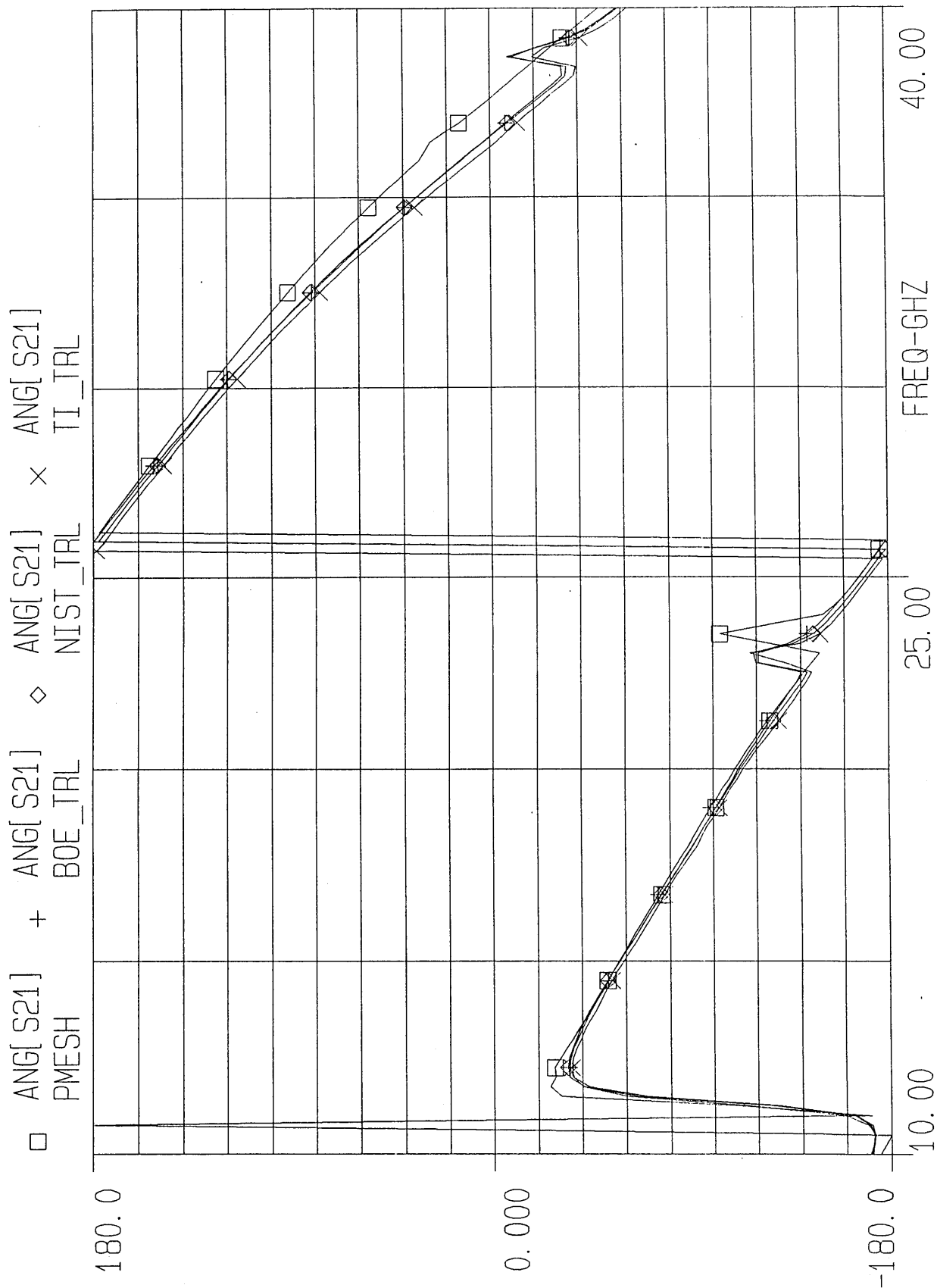


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□ MAG[S21] + MAG[S21] ◇ MAG[S21] × MAG[S21]
PMESH BOE_IRL NIST_IRL TI_IRL



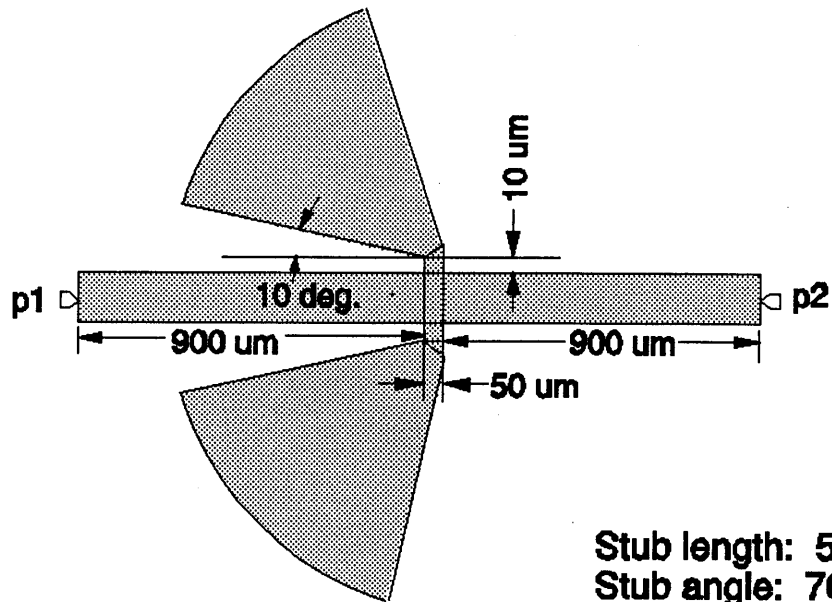
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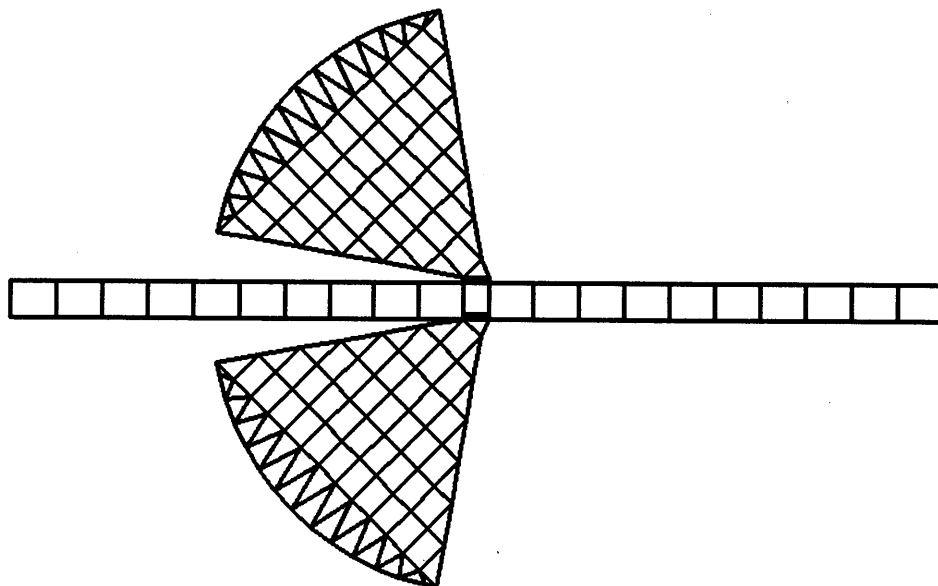
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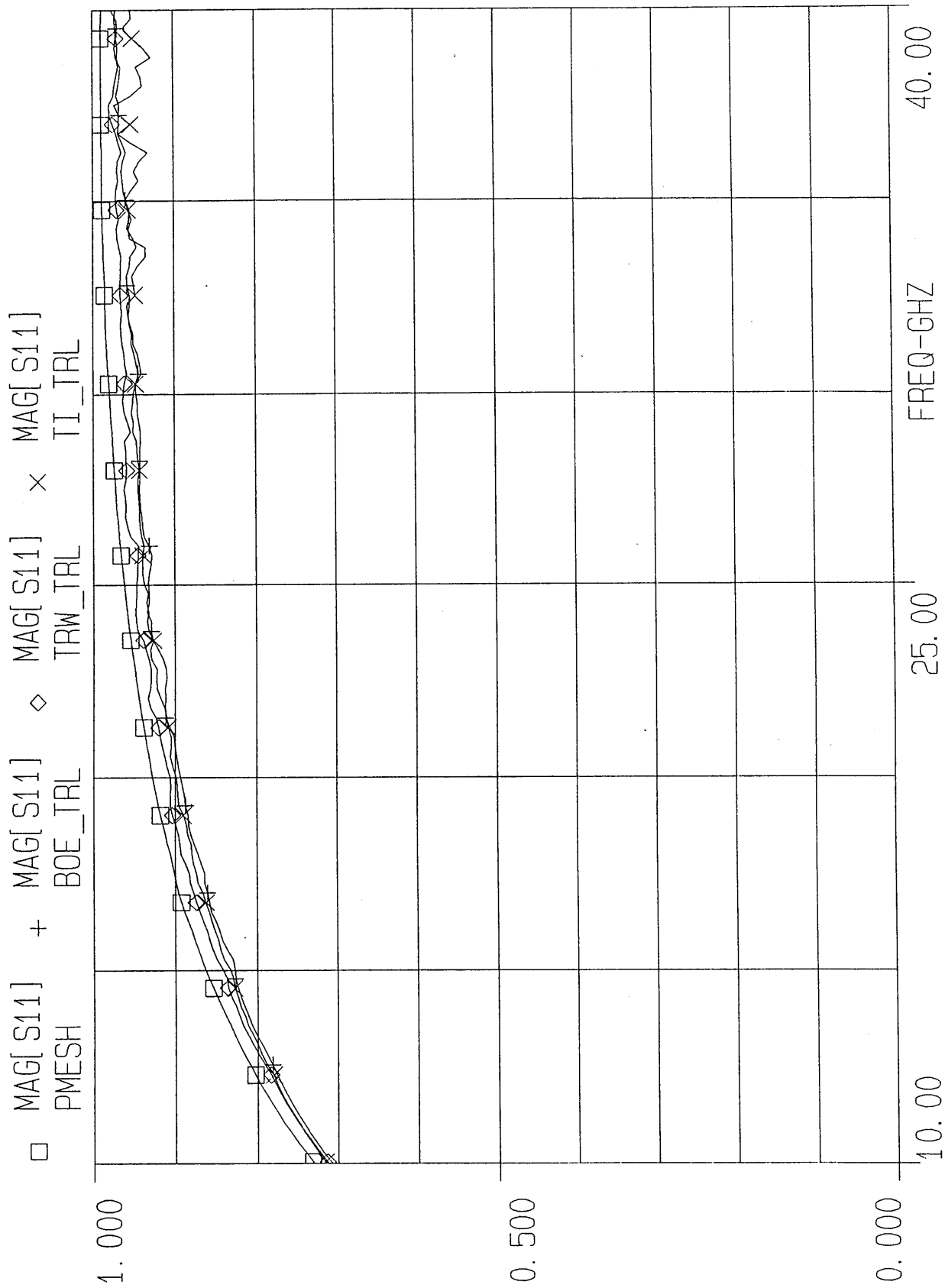


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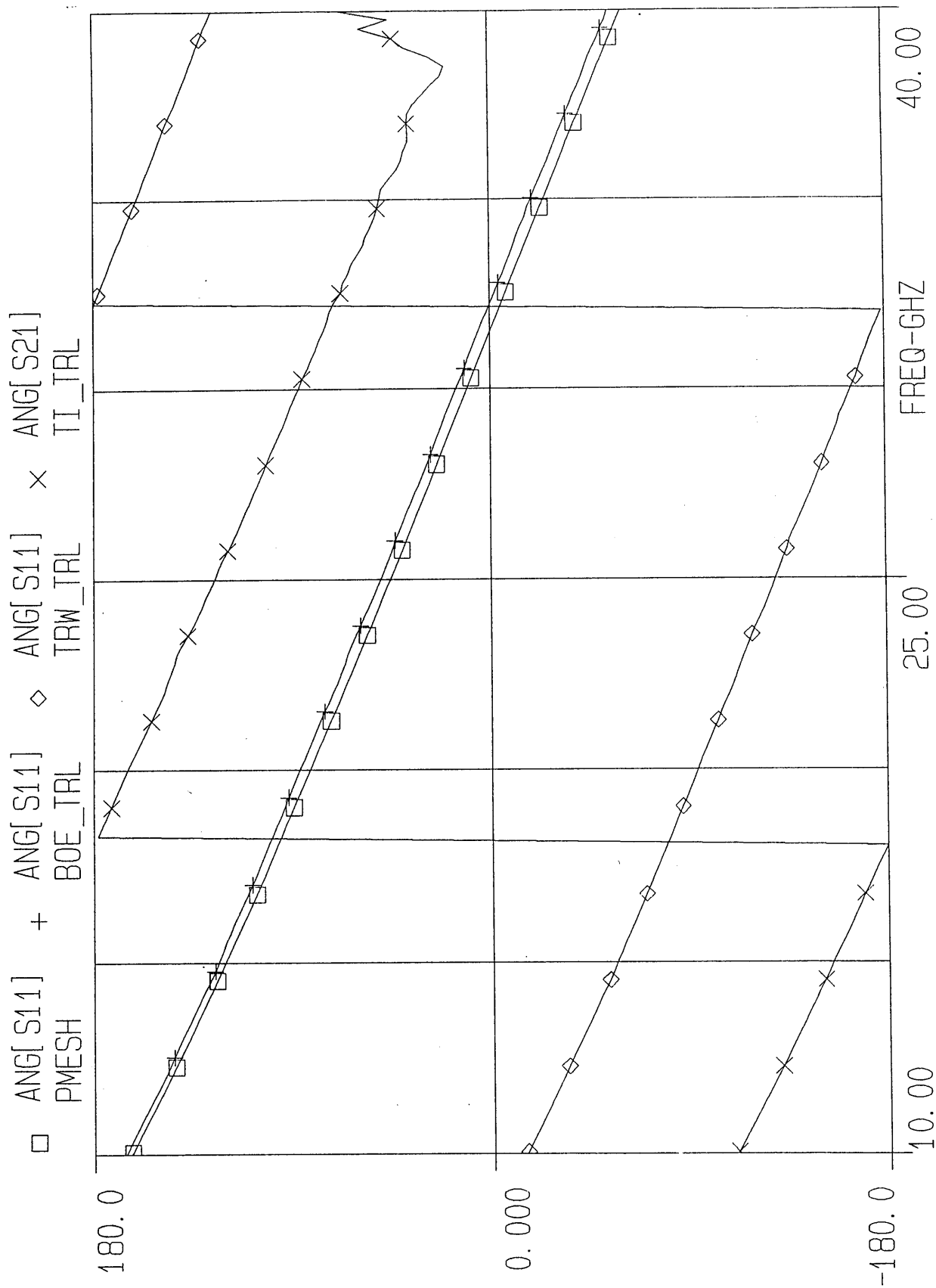
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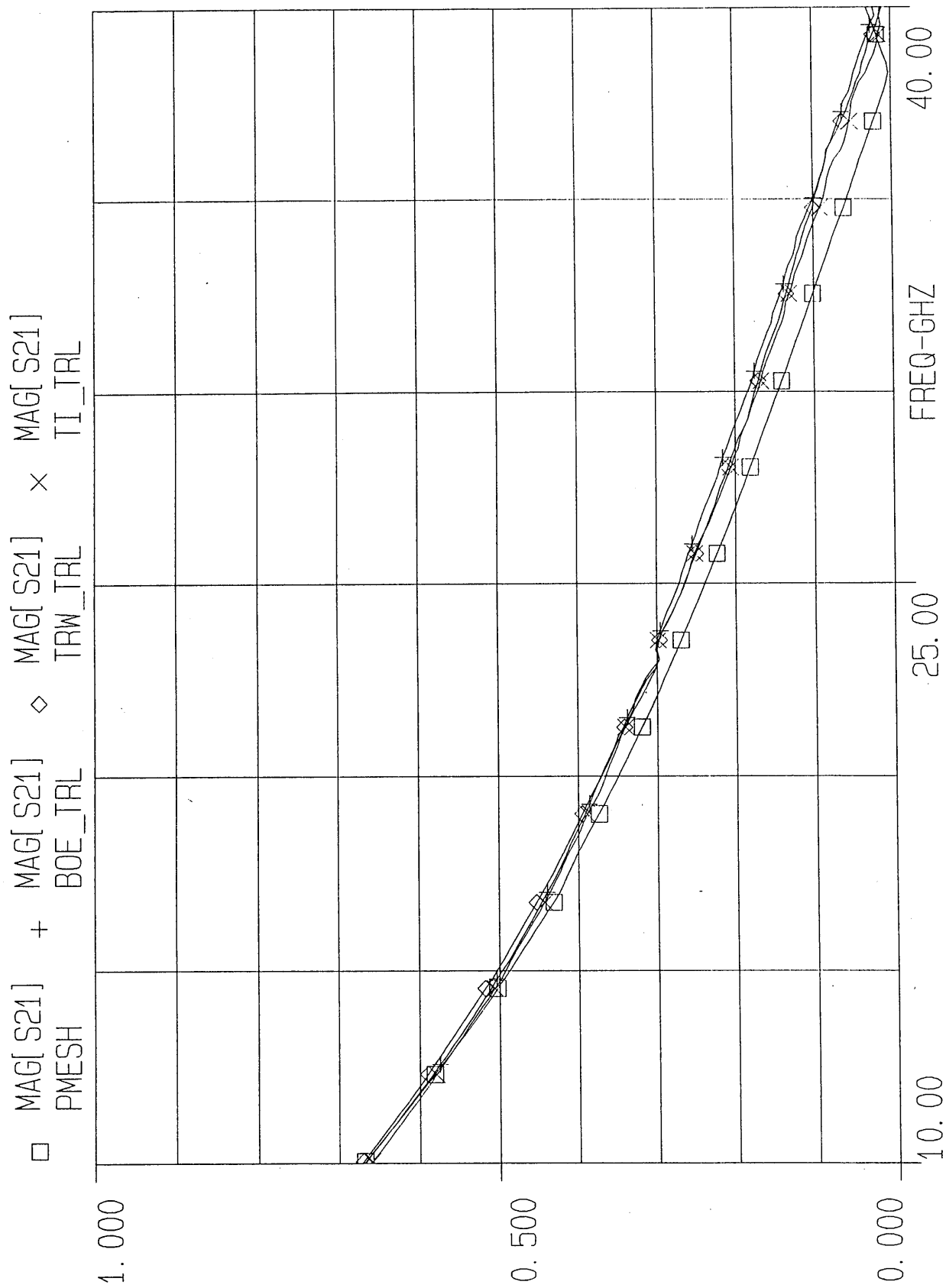
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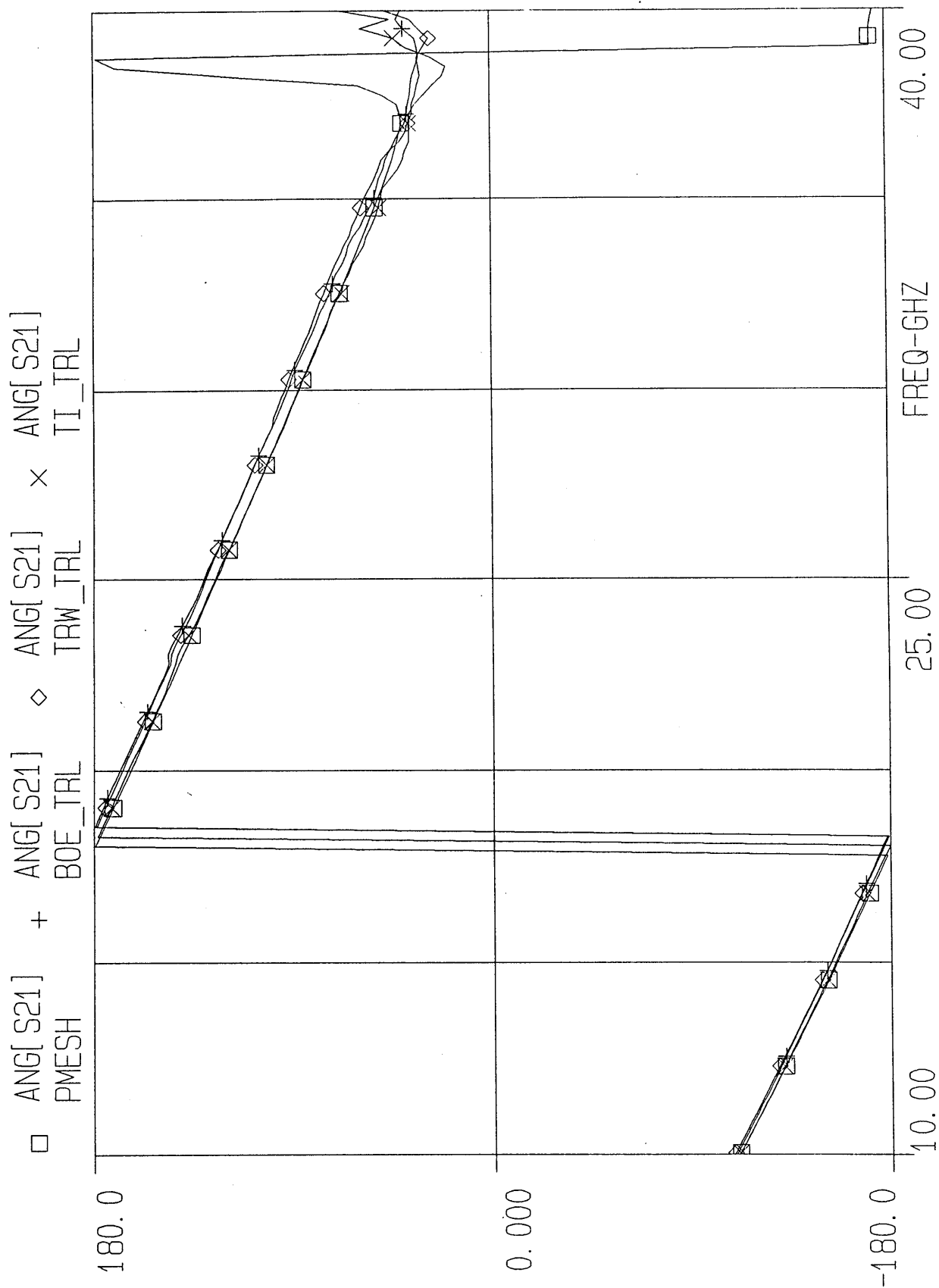
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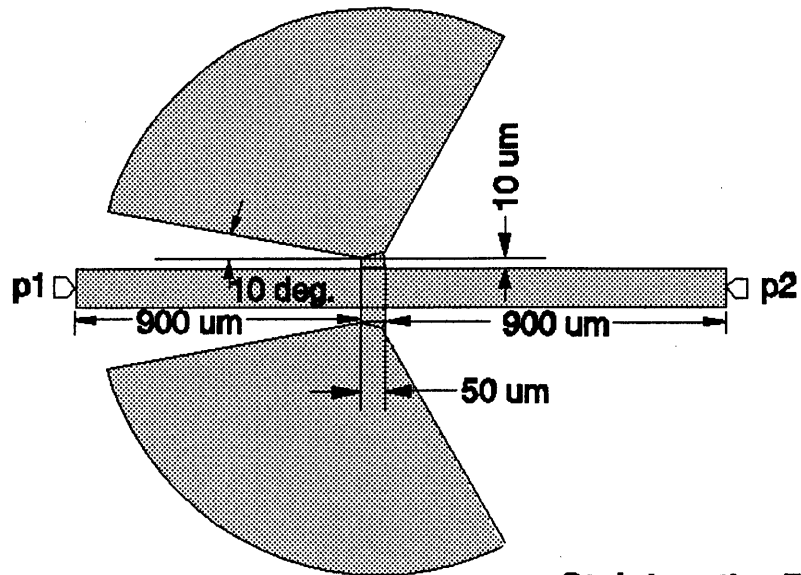


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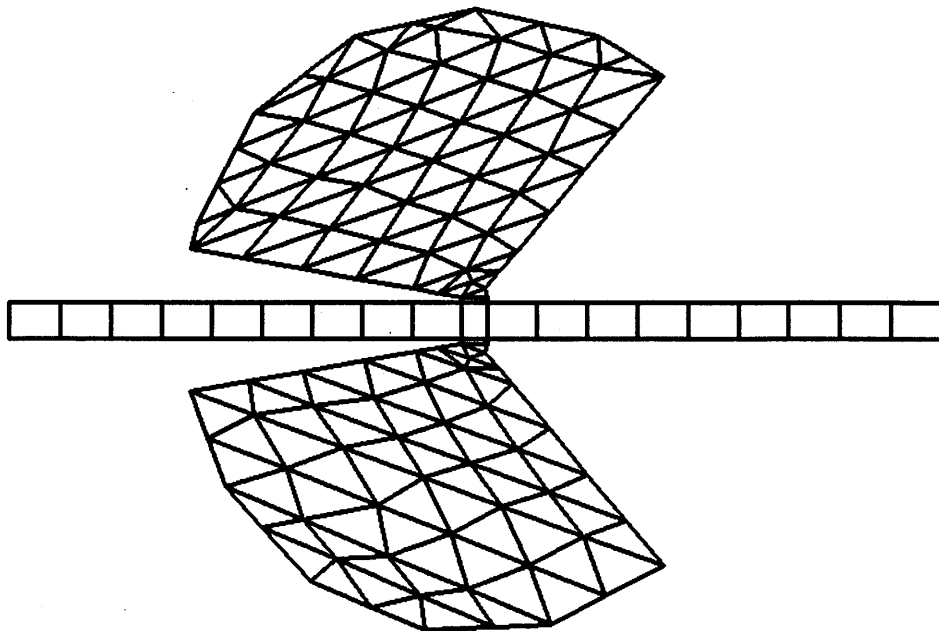
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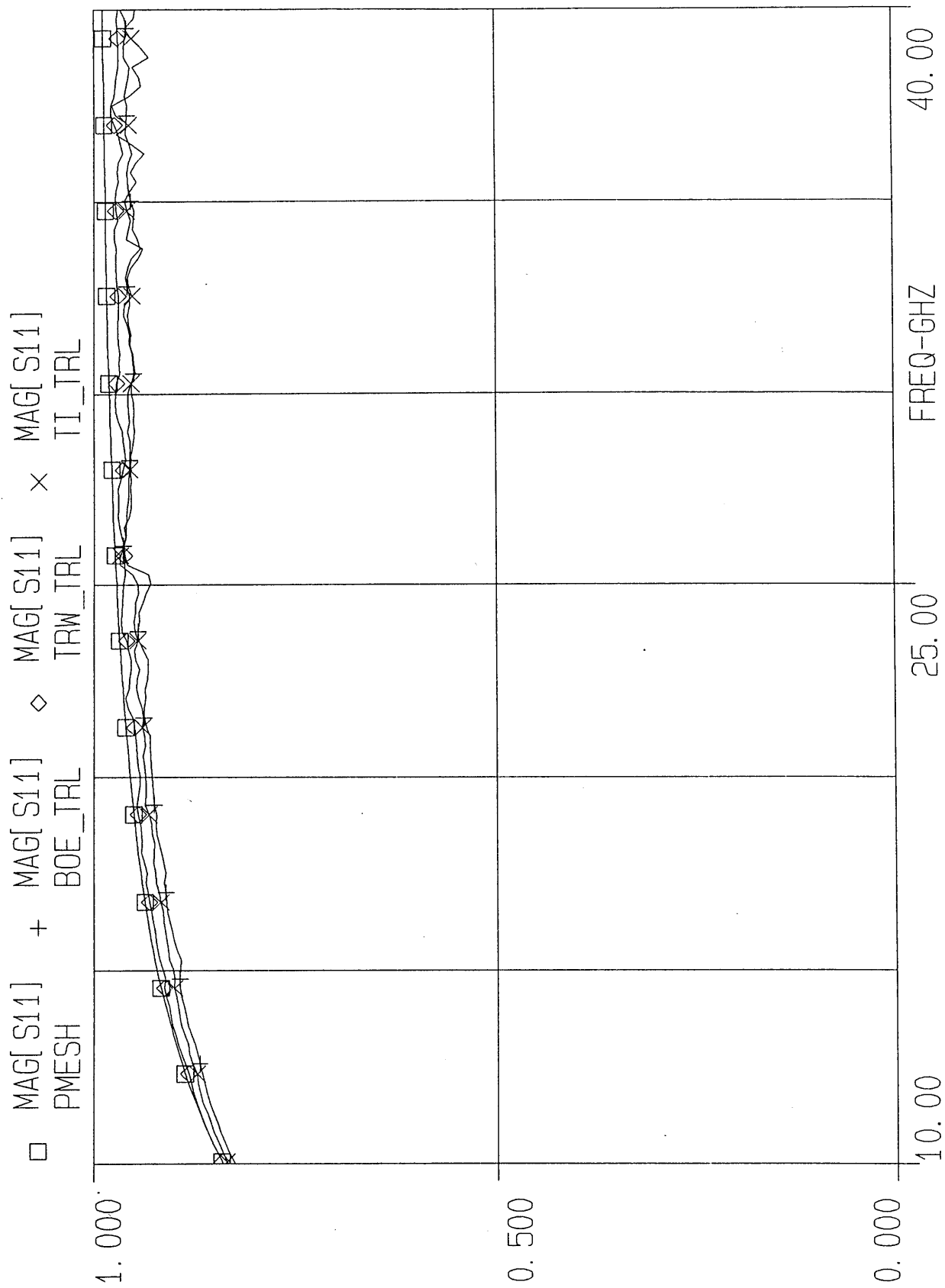


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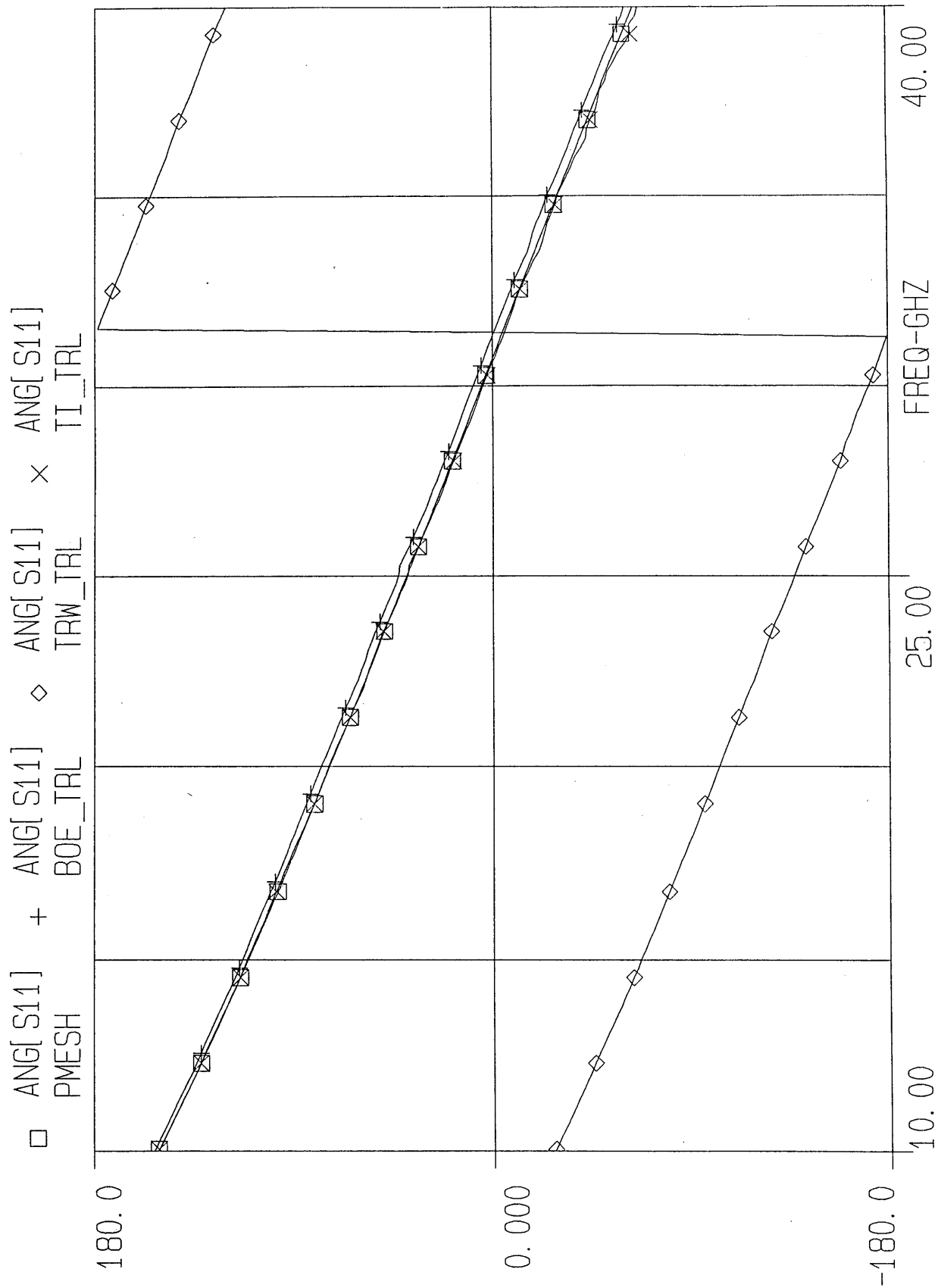
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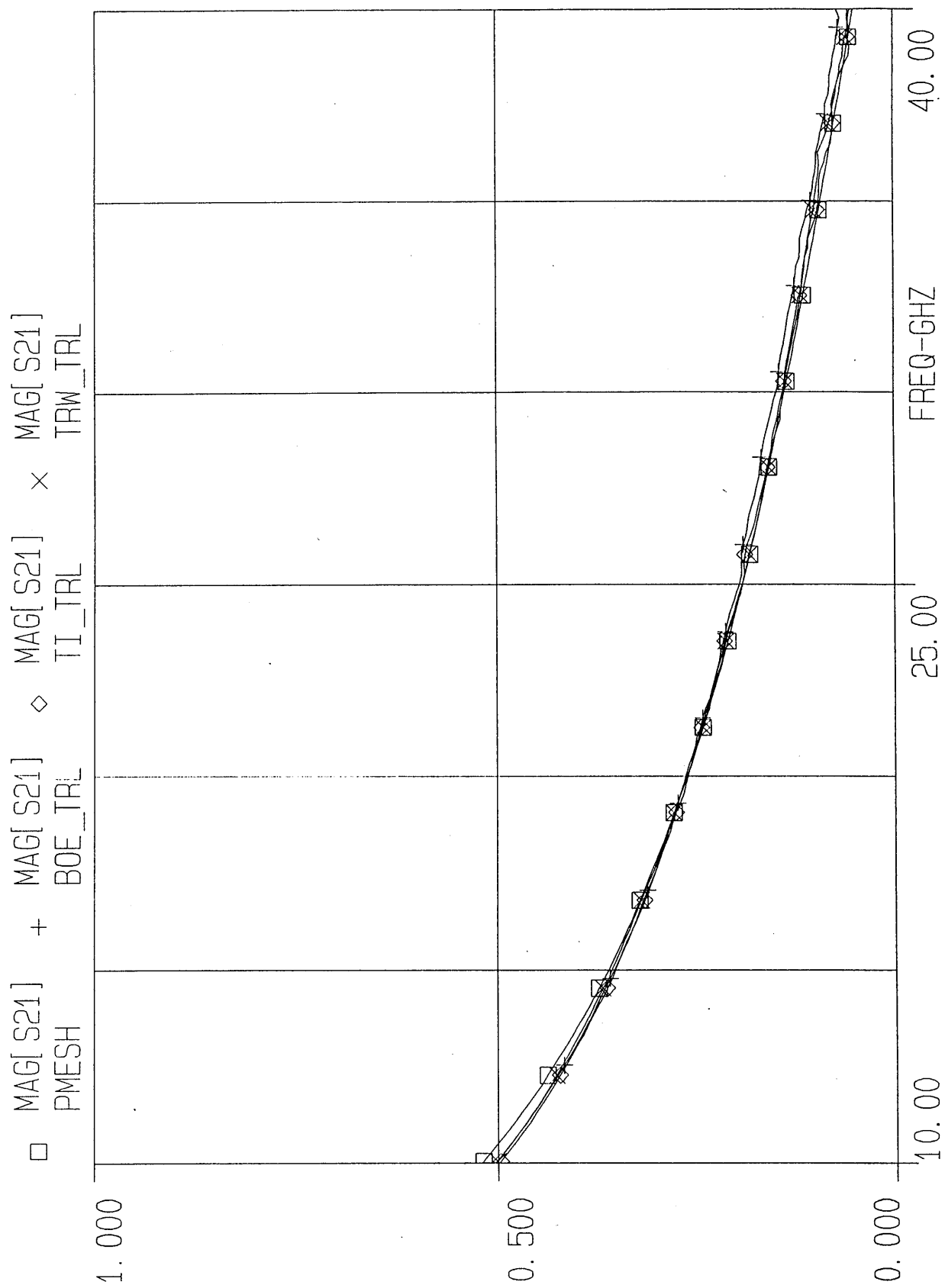
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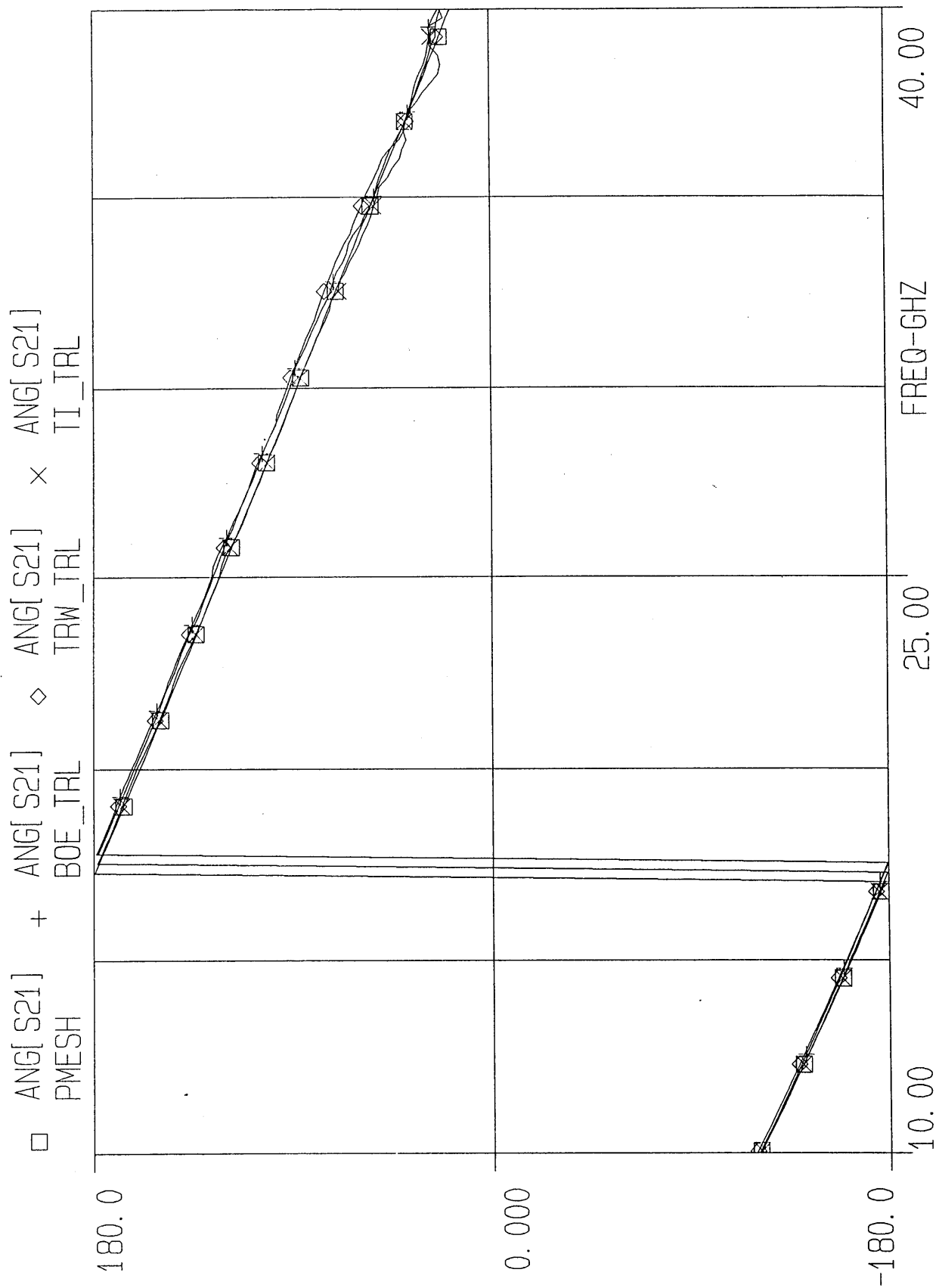
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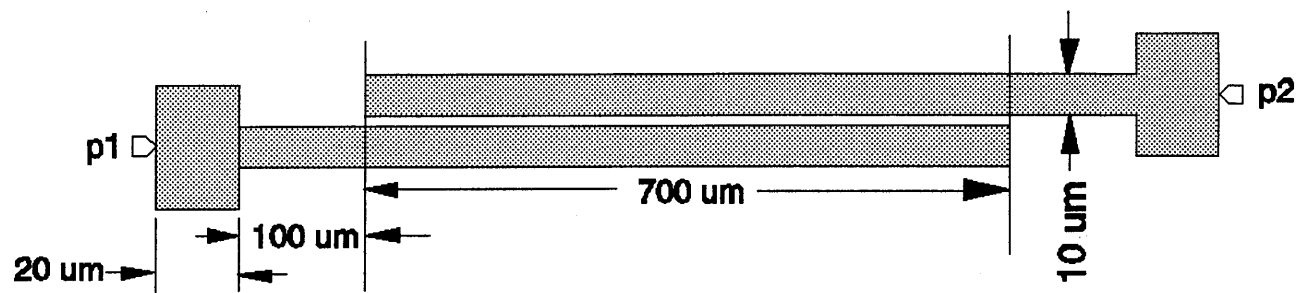


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7: DC Block
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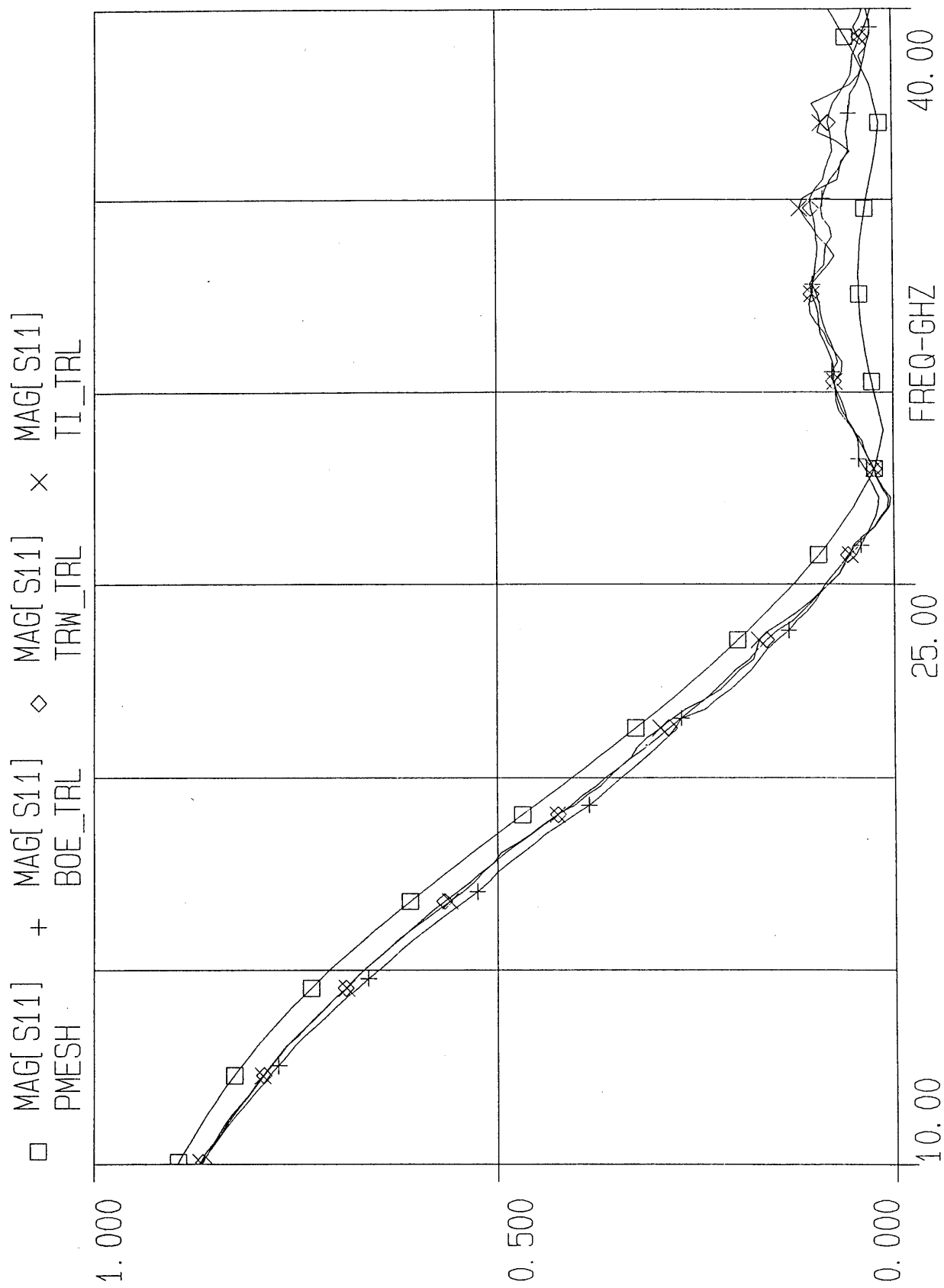


Gap: 5 μm
Feed line width: 73 μm

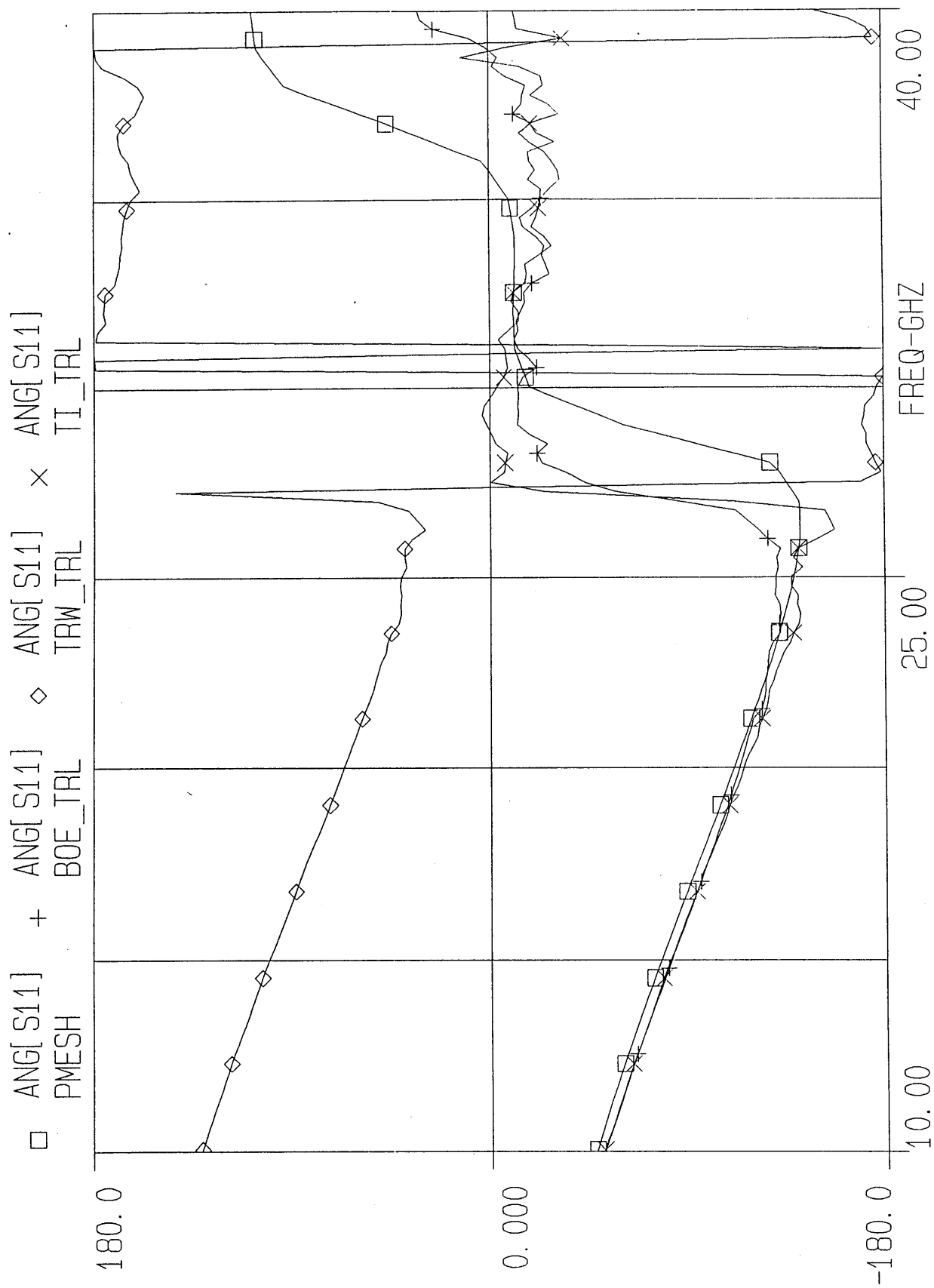
Gridded Geometry:



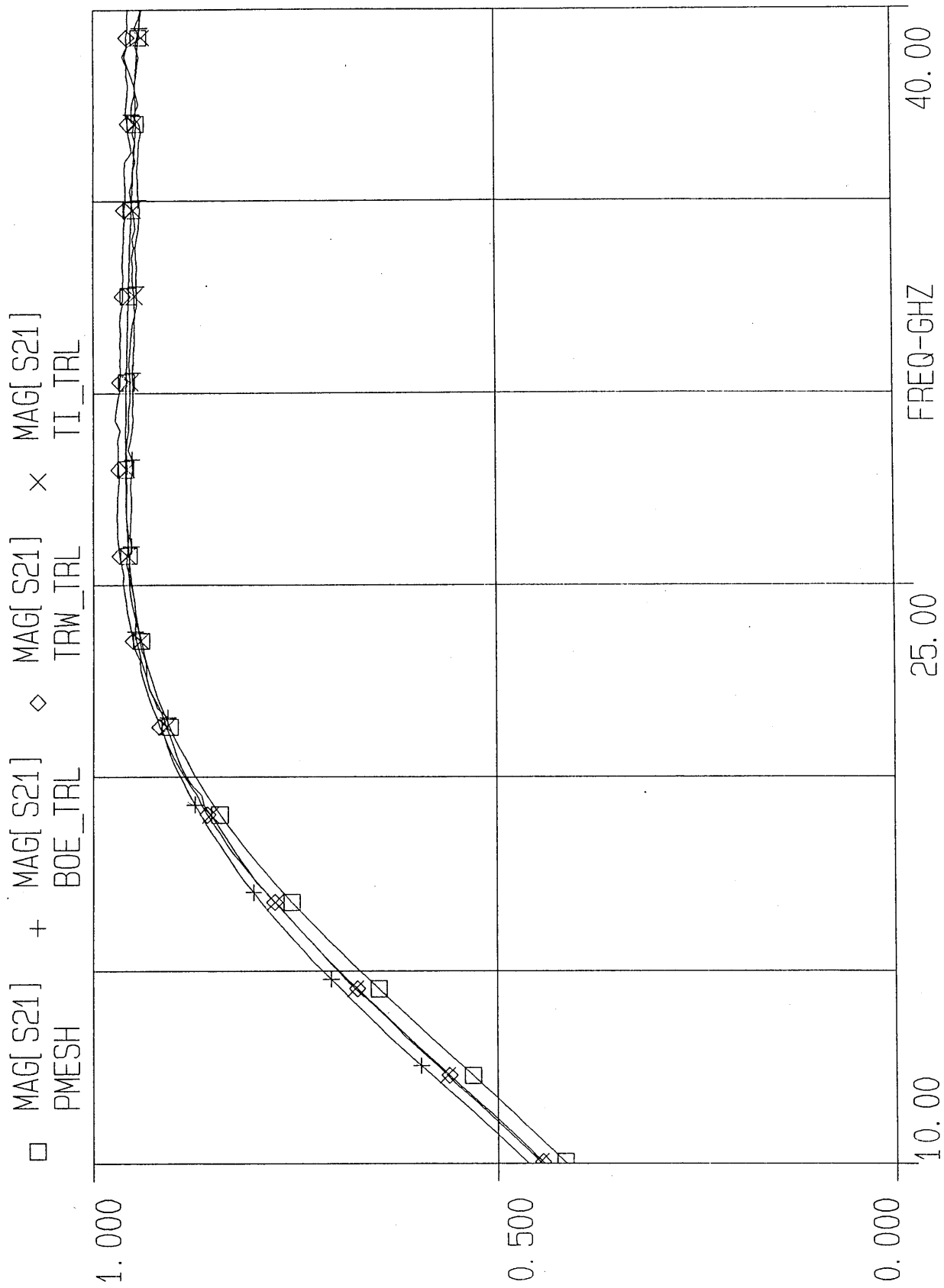
EEsof - Libra - Sun Oct 25 12:36:24 1992 - dc_block



EEsof - Libra - Sun Oct 25 12:36:24 1992 - dc_block

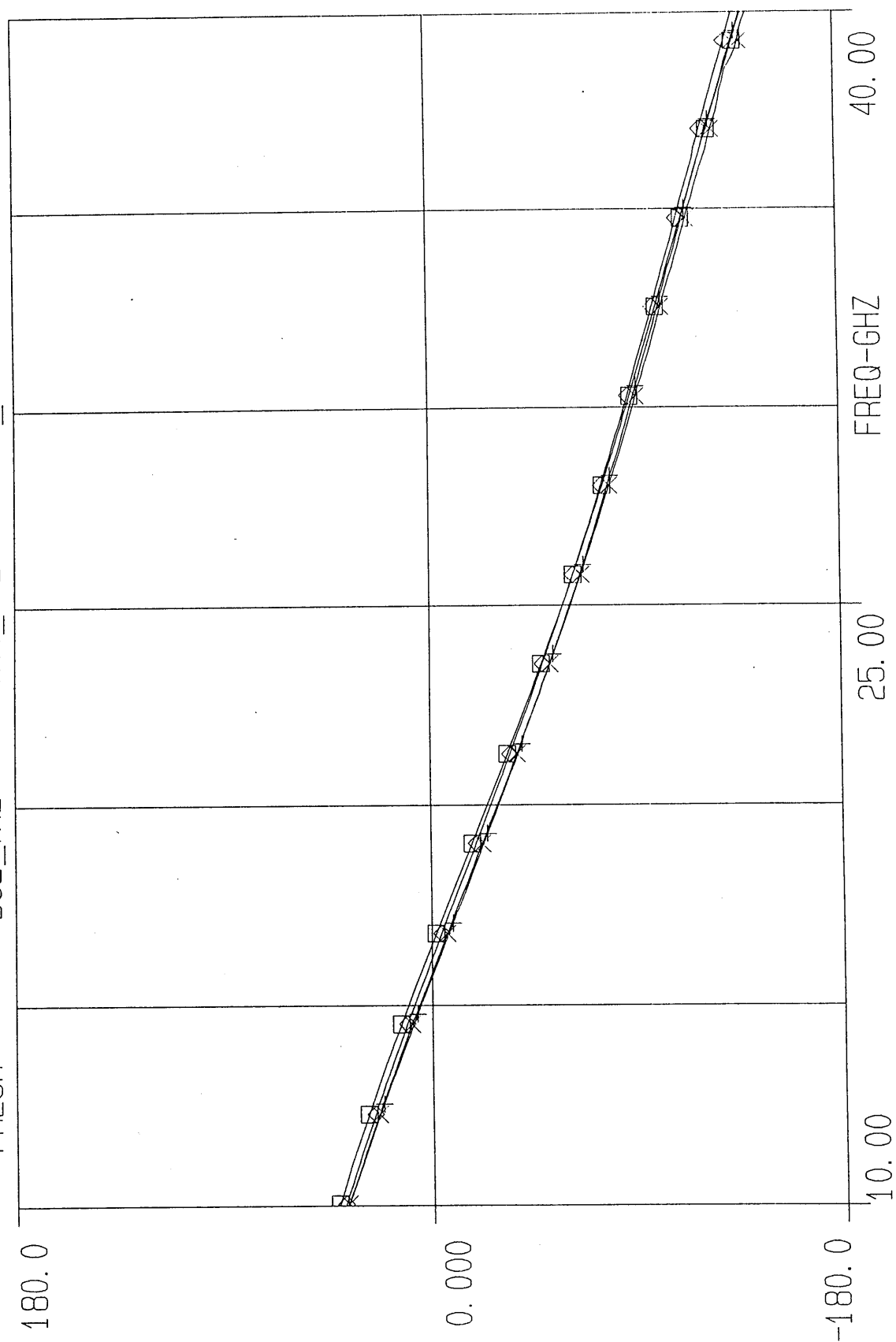


EEsof - Libra - Sun Oct 25 12:36:22 1992 - dc_block



EEsof - Libra - Sun Oct 25 12:36:22 1992 - dc_block

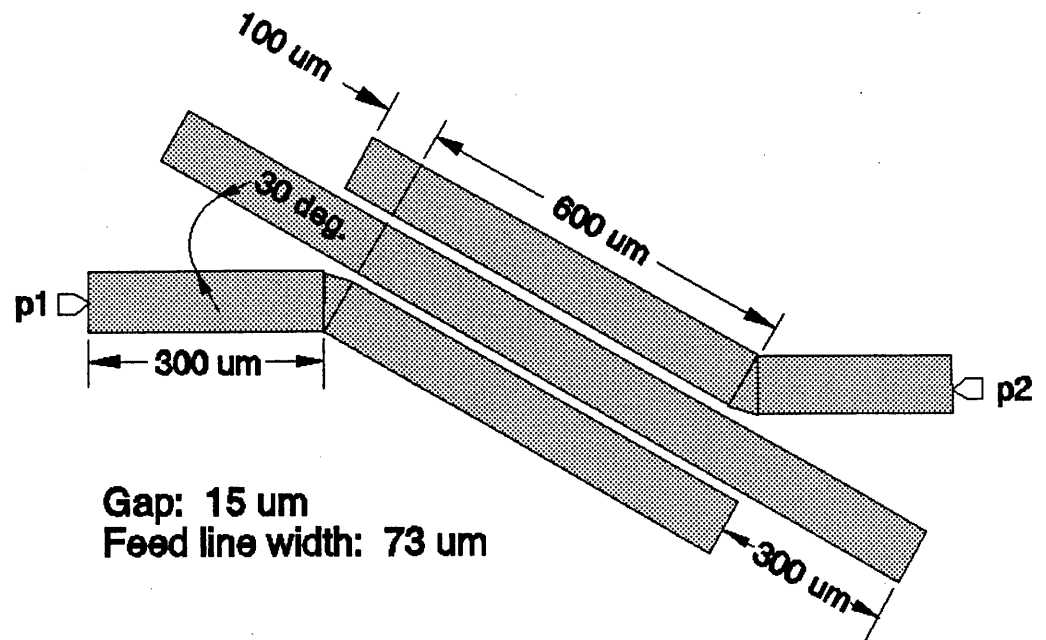
□ ANG[S21] + ANG[S21] × ANG[S21]
PMESH BOE_TRL TI_TRL



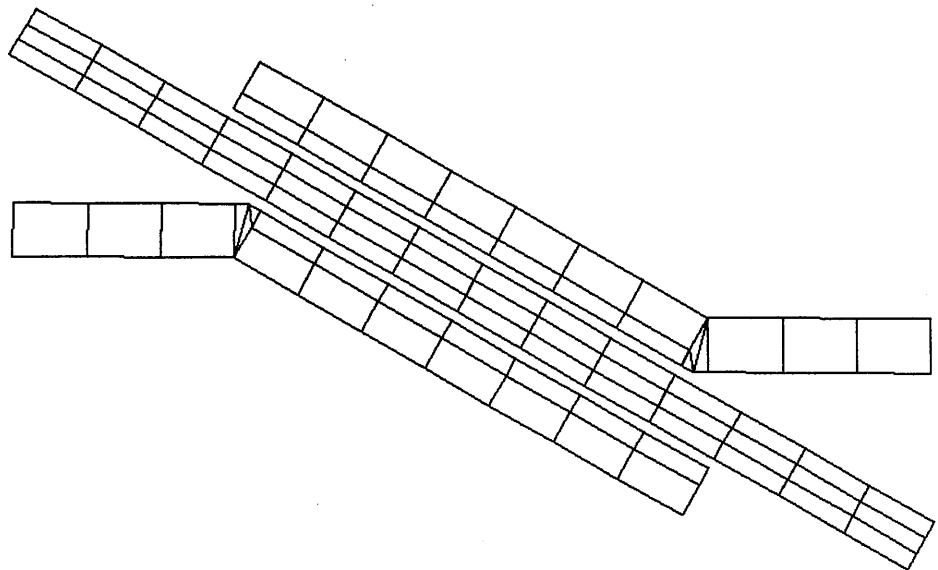
8: Band Pass Filter

Label: filter2

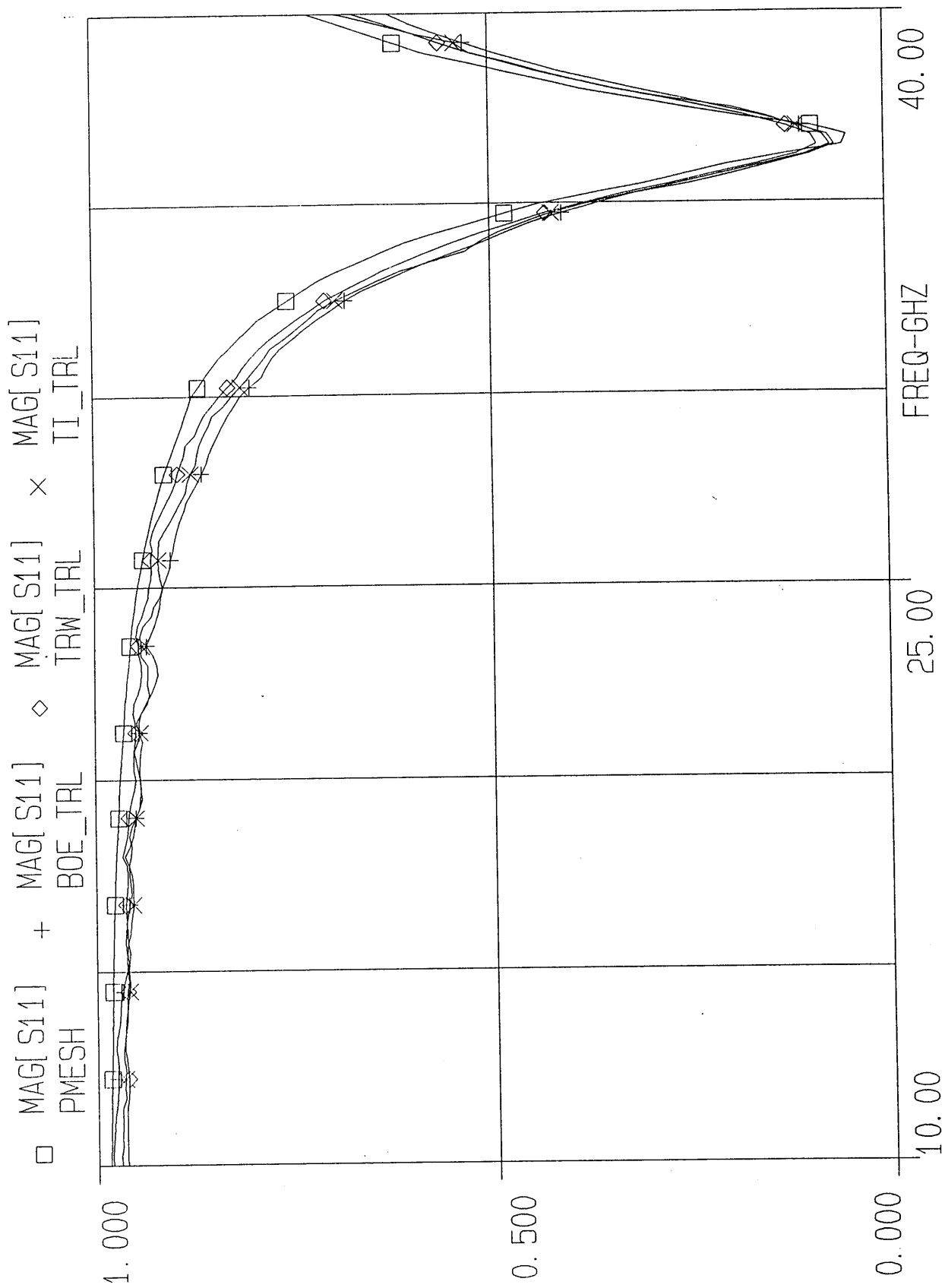
Dimensions:



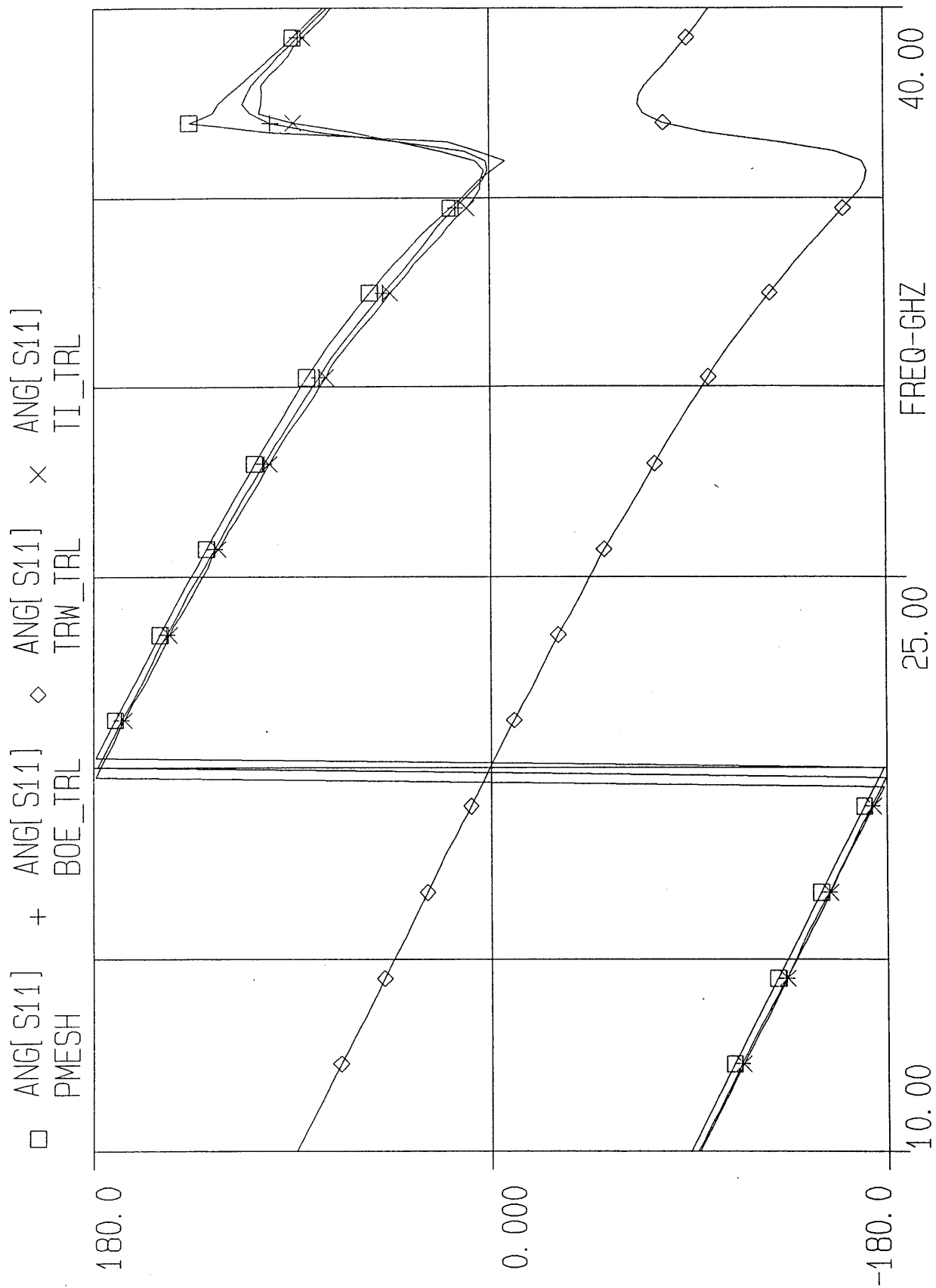
Gridded Geometry:



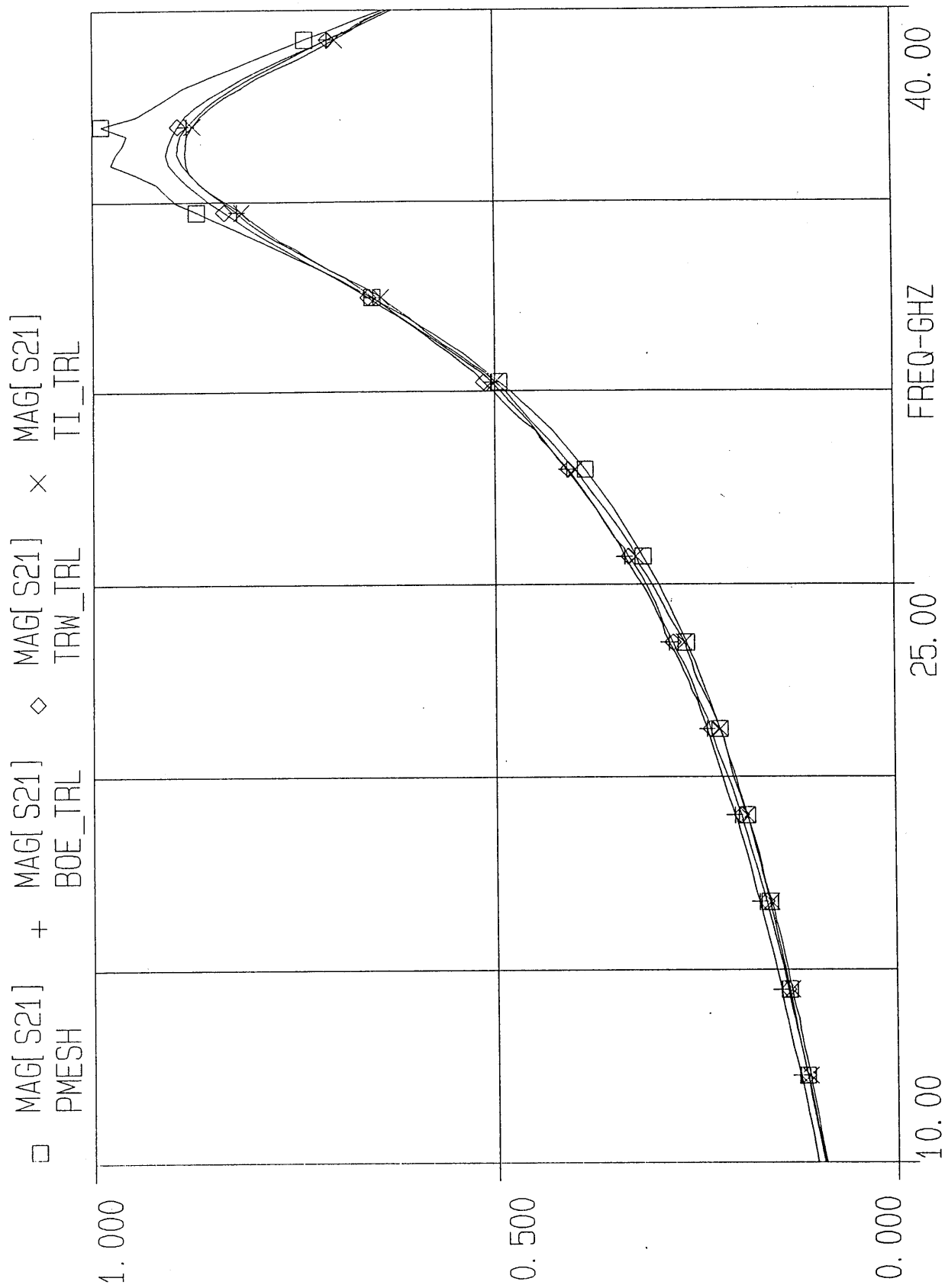
EEsof - Libra - Sun Oct 25 12:41:35 1992 - filter2



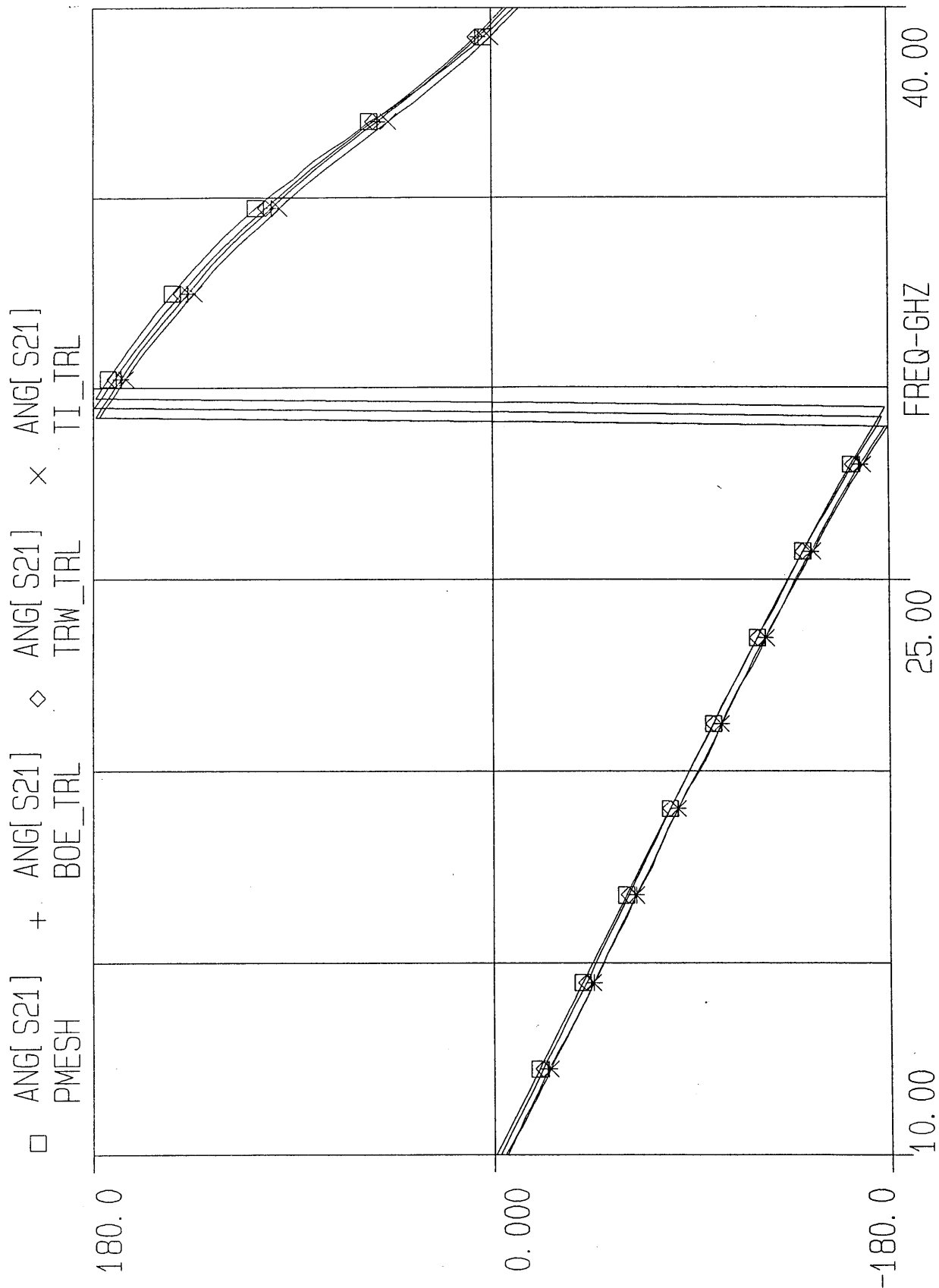
EEsof - Libra - Sun Oct 25 12:41:36 1992 - filter2



EEsof - Libra - Sun Oct 25 12:41:33 1992 - filter2



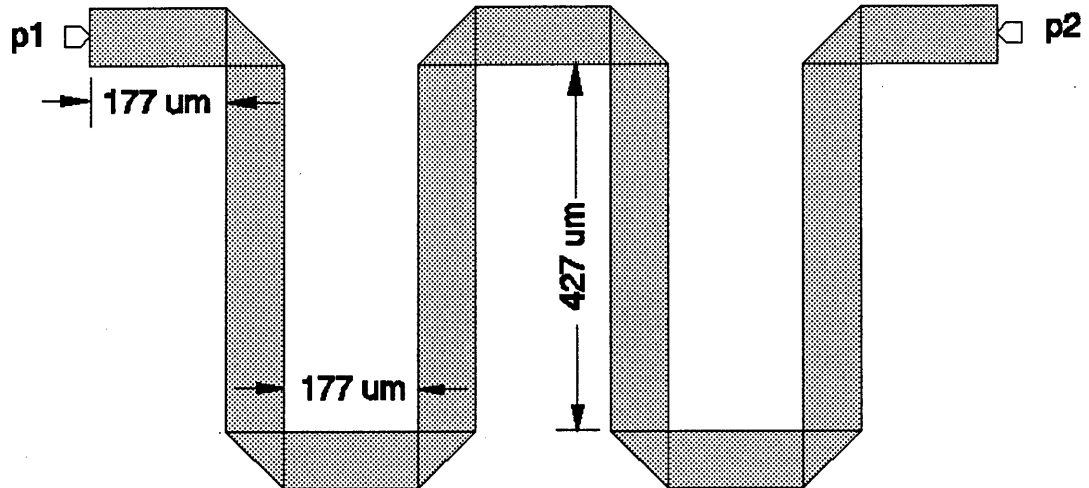
EEsof - Libra - Sun Oct 25 12:41:33 1992 - filter2



9: 90° Microstrip Bends

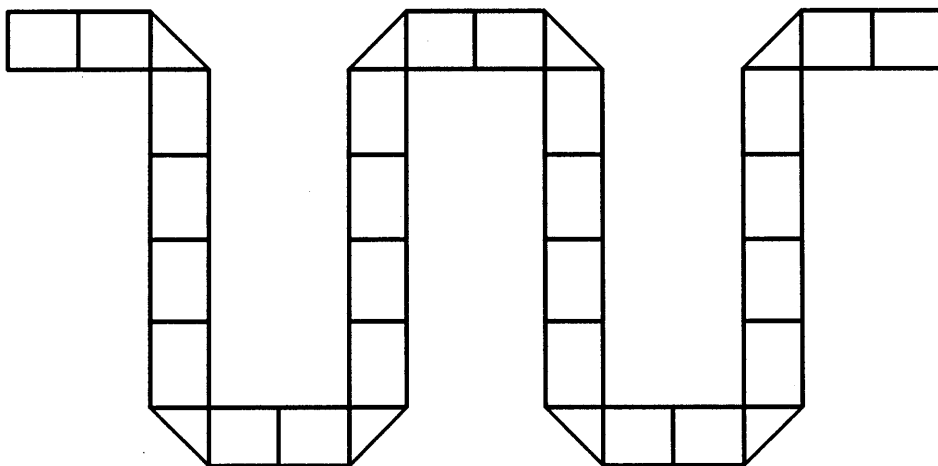
Label: bends

Dimensions:

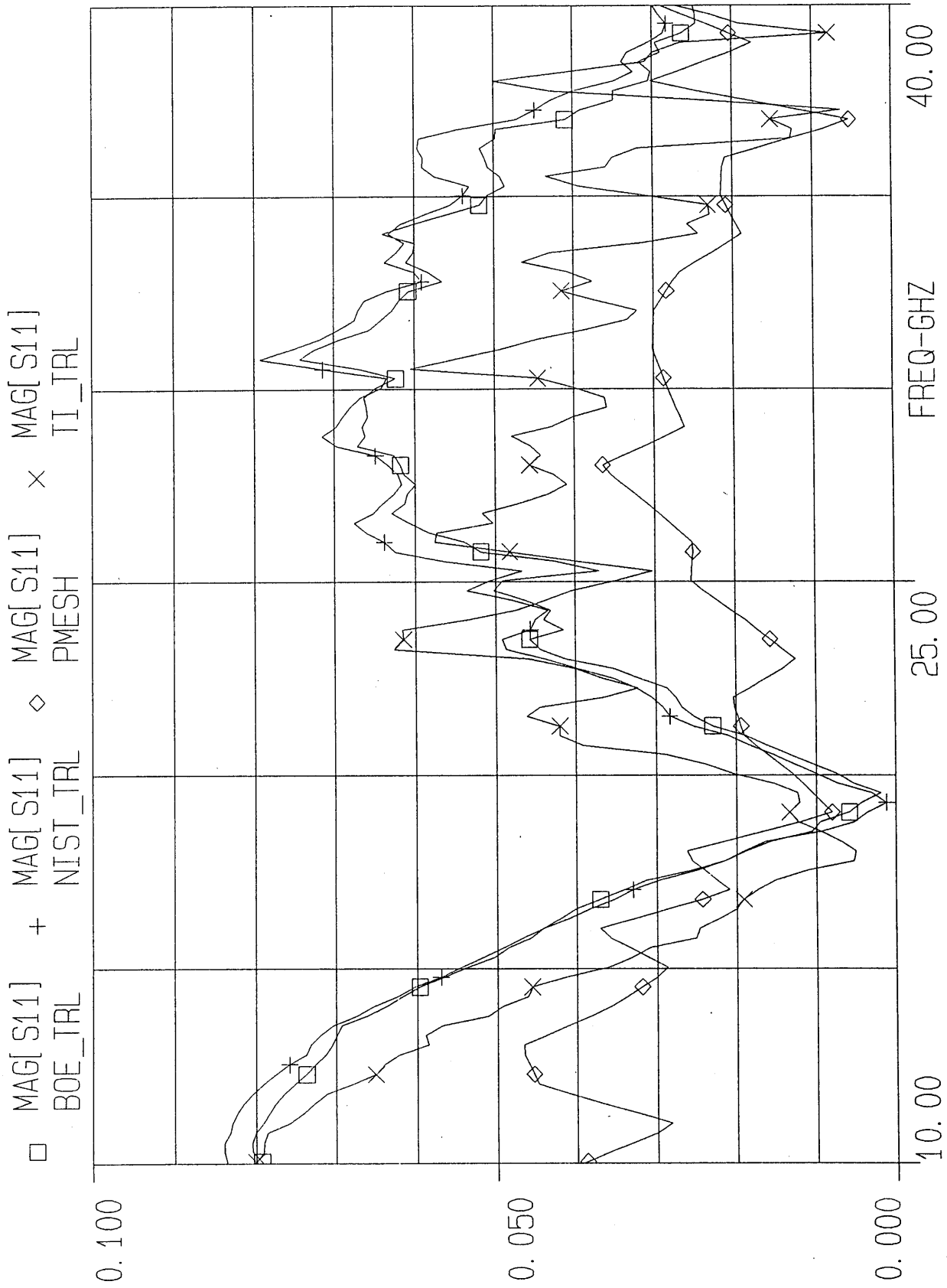


Feed line width: 73 μm
Total line length: 3178 μm

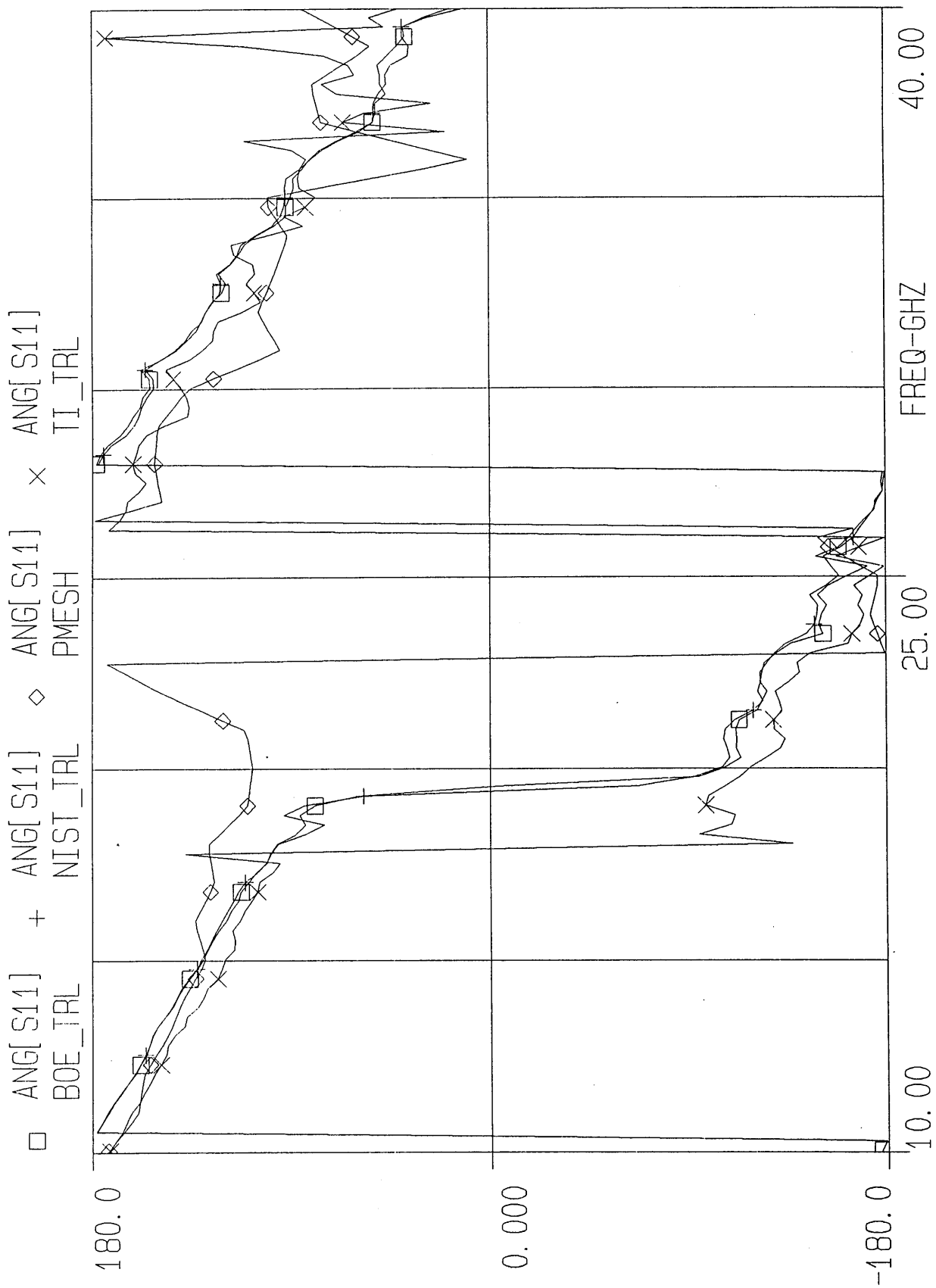
Gridded Geometry:



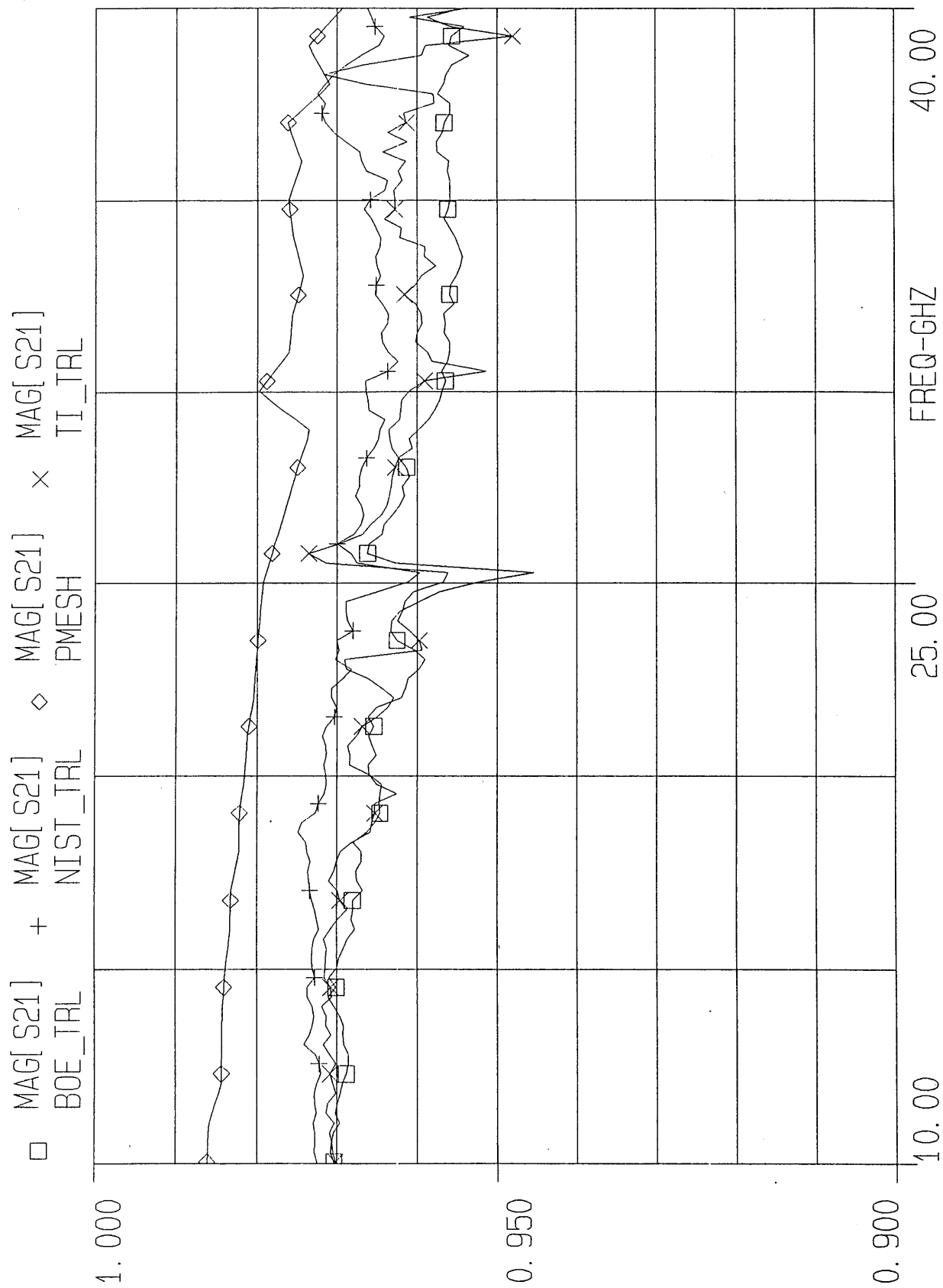
EEsof - Libra - Sun Oct 25 12:53:22 1992 - bends



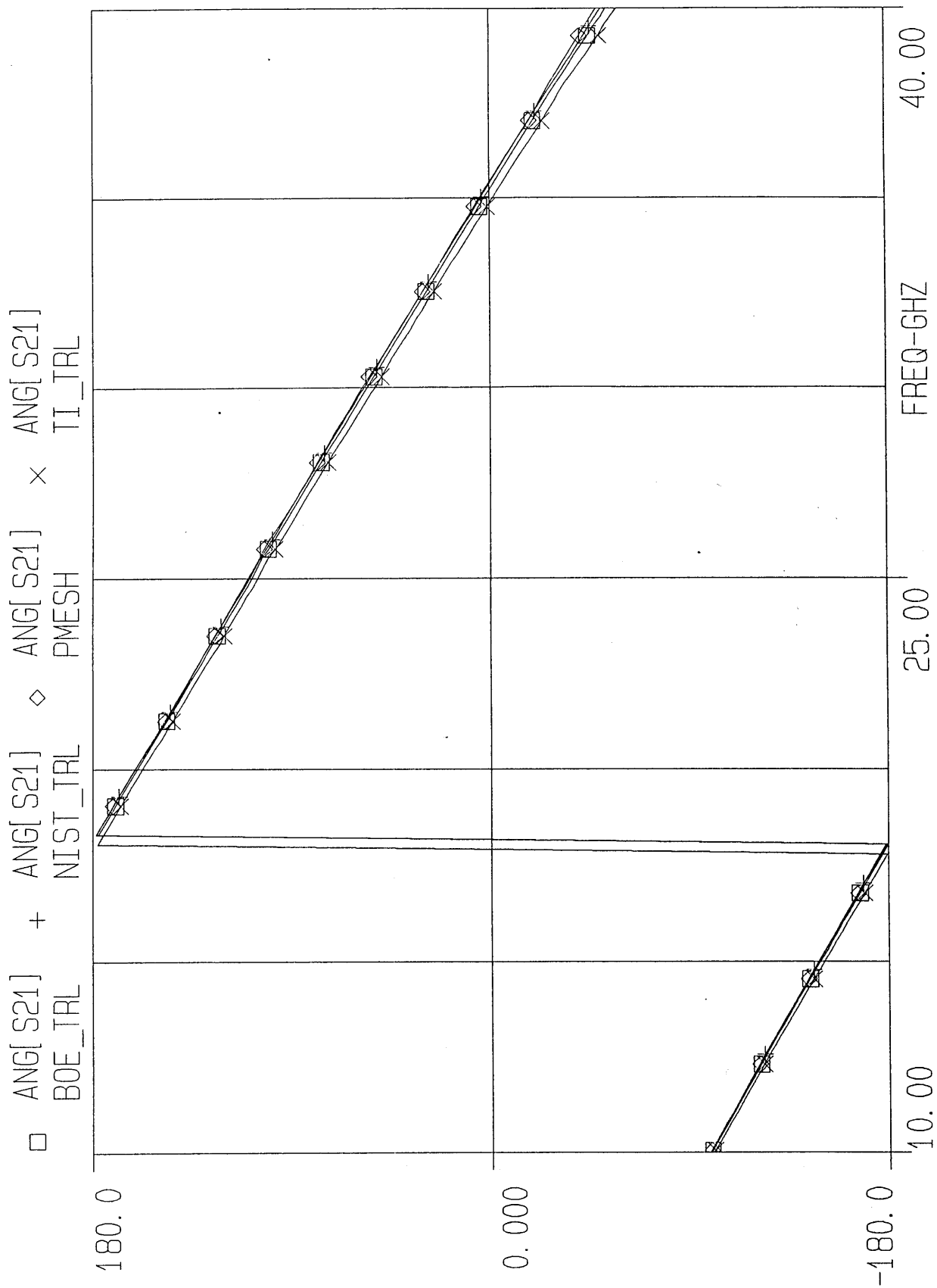
EEsof - Libra - Sun Oct 25 12:53:23 1992 - bends



EEsof - Libra - Sun Oct 25 12:53:20 1992 - bends



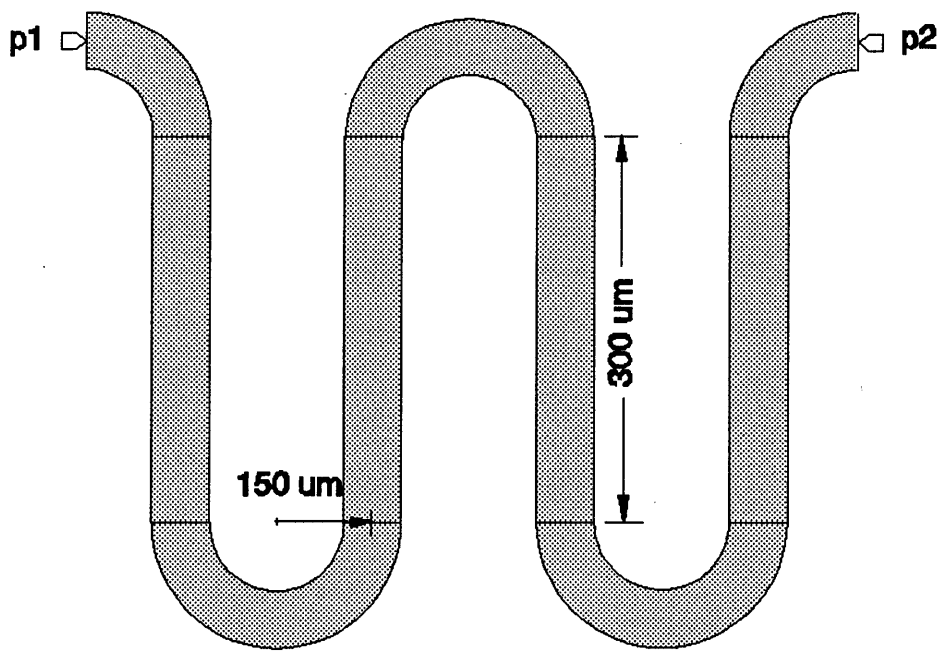
EEsof - Libra - Sun Oct 25 12:53:21 1992 - bends



10: Microstrip Bends

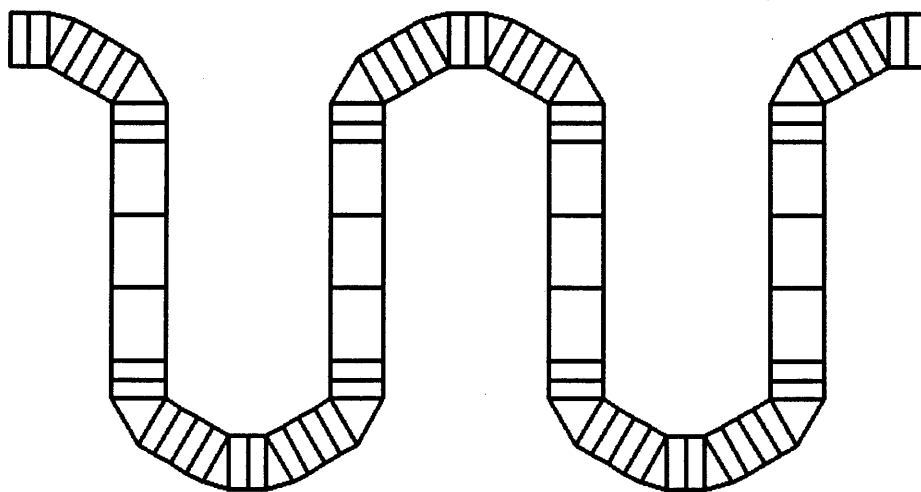
Label: meander

Dimensions:

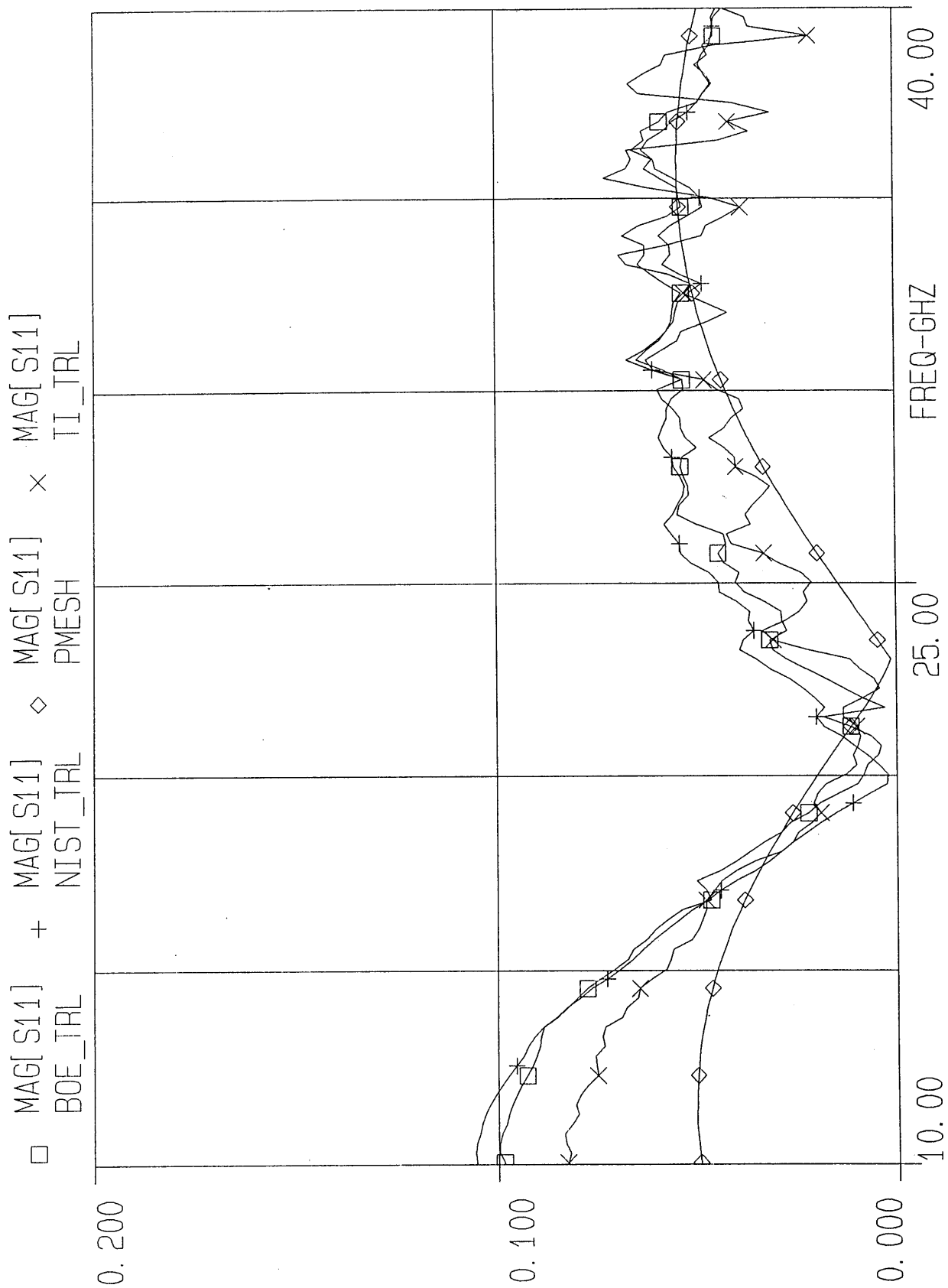


Feed line width: 73 μm
Total line length: 3084 μm

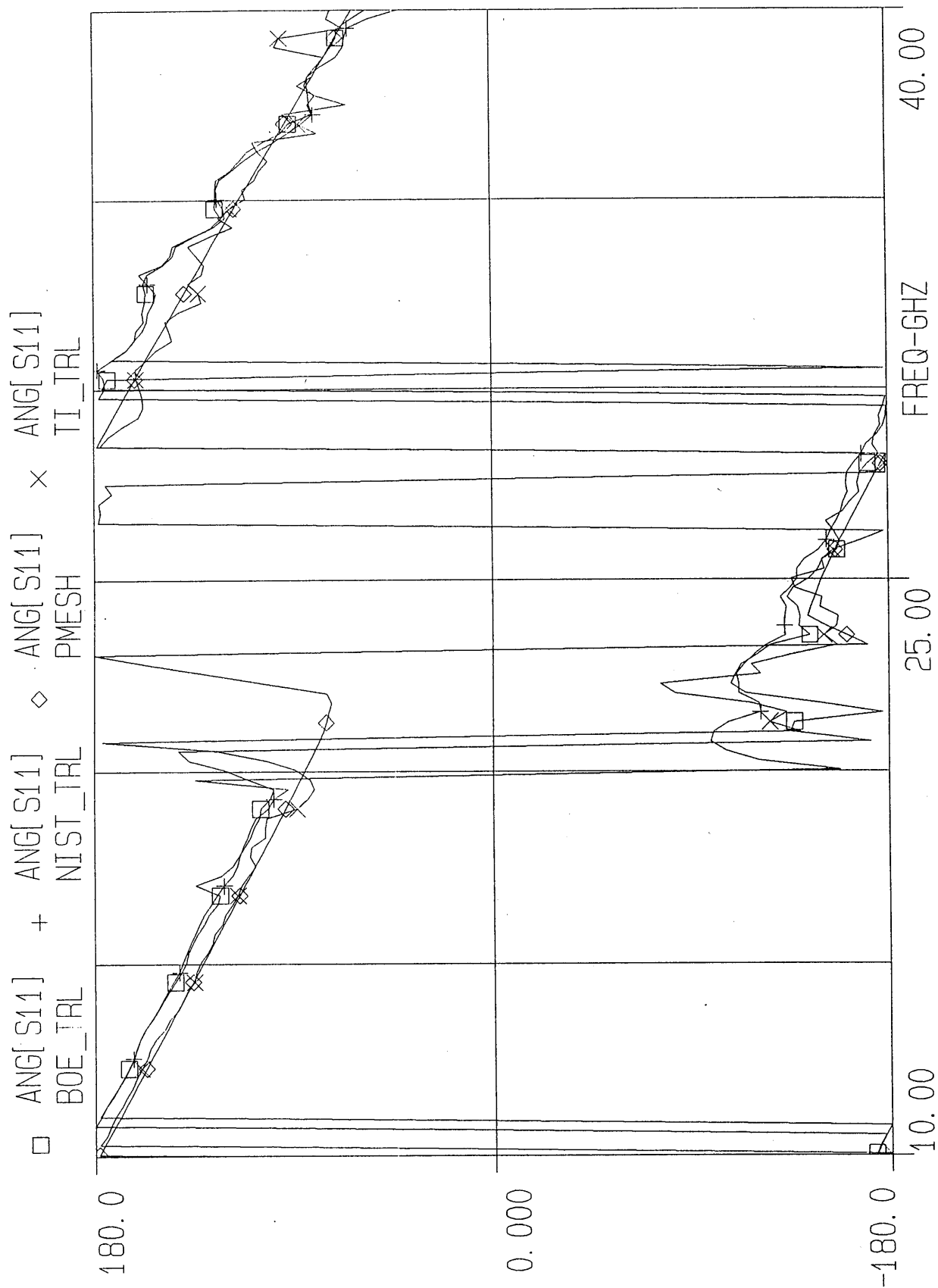
Gridded Geometry:



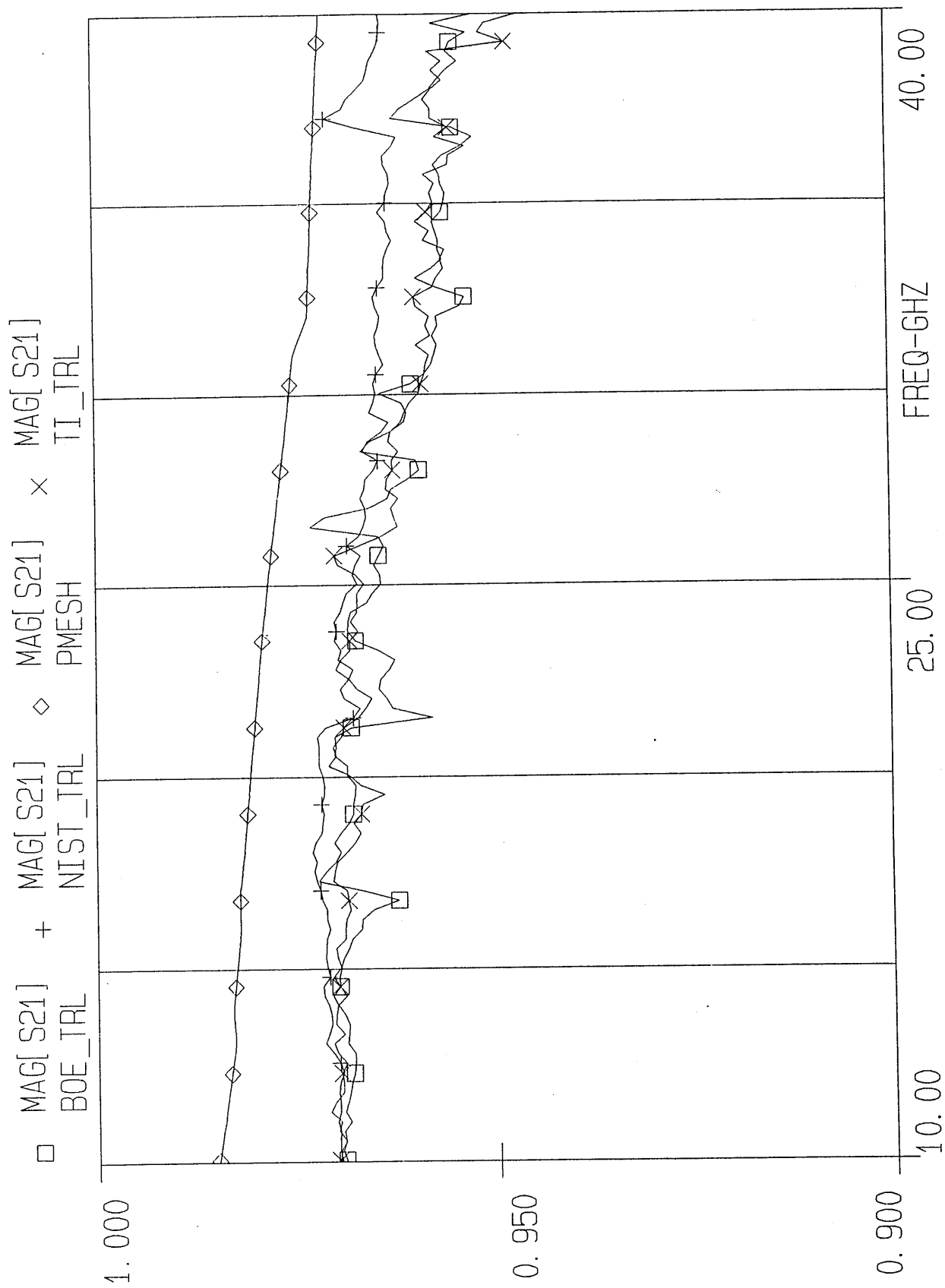
EEsof - Libra - Sun Oct 25 13:01:53 1992 - meander



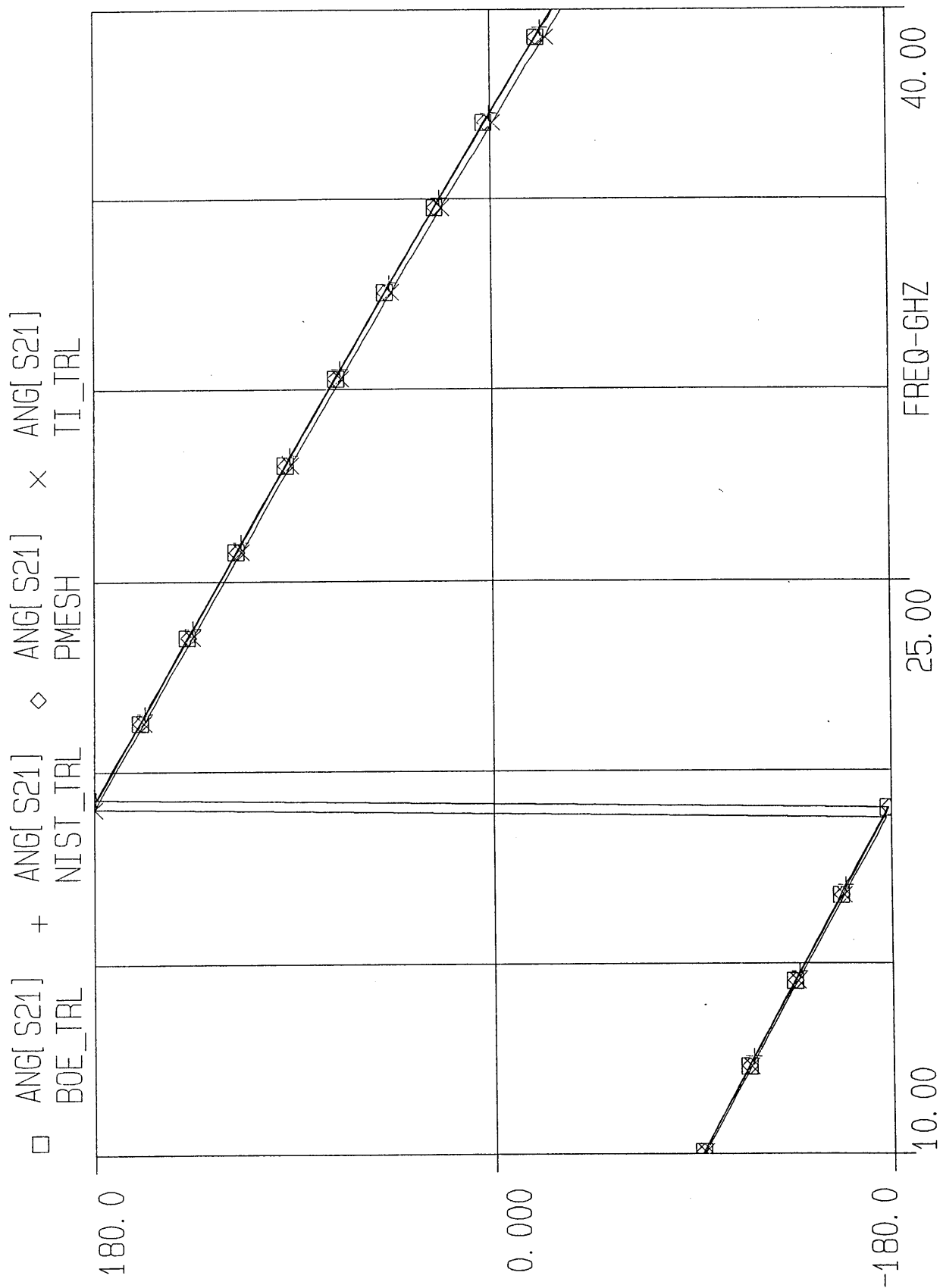
EEsof - Libra - Sun Oct 25 13:01:55 1992 - meander



EEsof - Libra - Sun Oct 25 13:01:52 1992 - meander



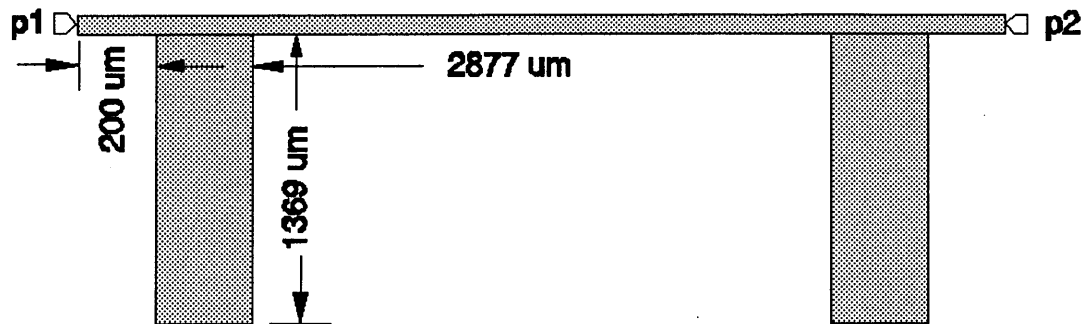
EEsof - Libra - Sun Oct 25 13:01:52 1992 - meander



11: Shunt Stubs

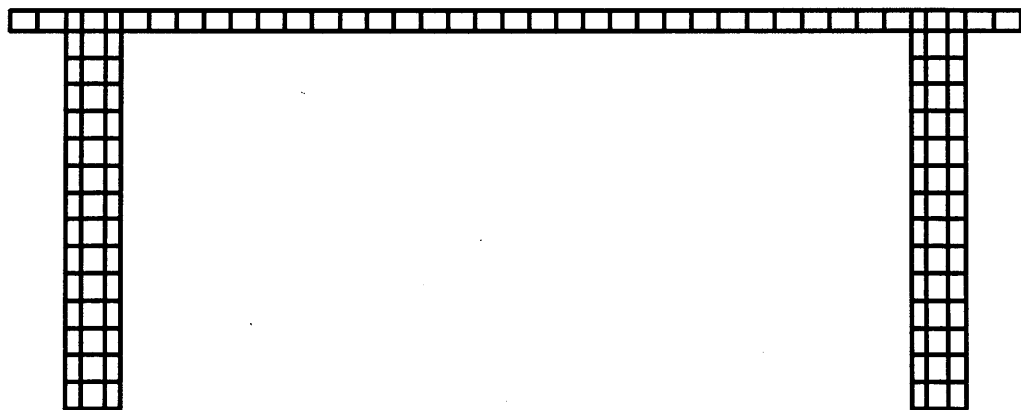
Label: sh_stubs

Dimensions:



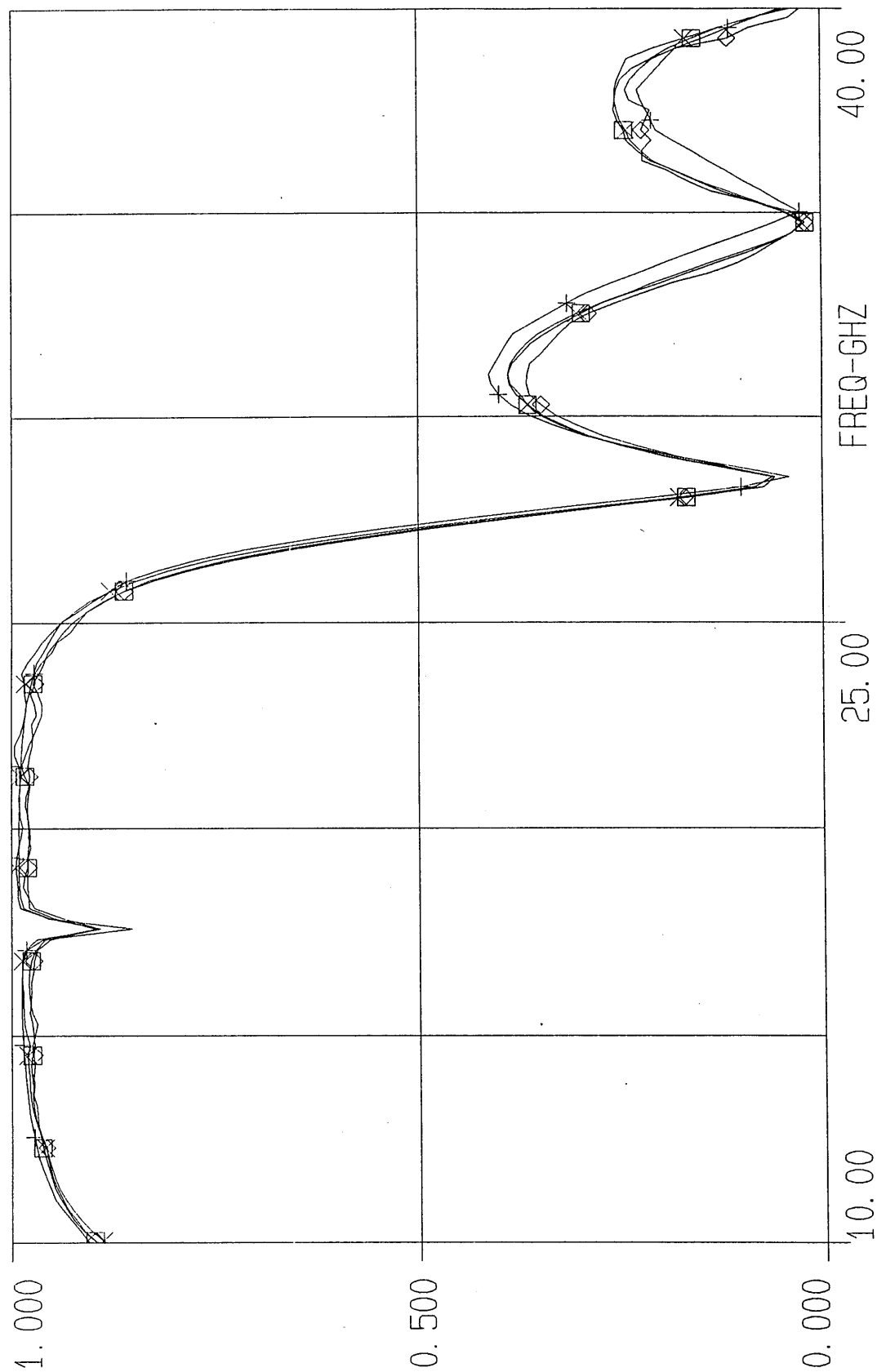
Feed line width: 73 μm
shunt stub width: 200 μm

Gridded Geometry:



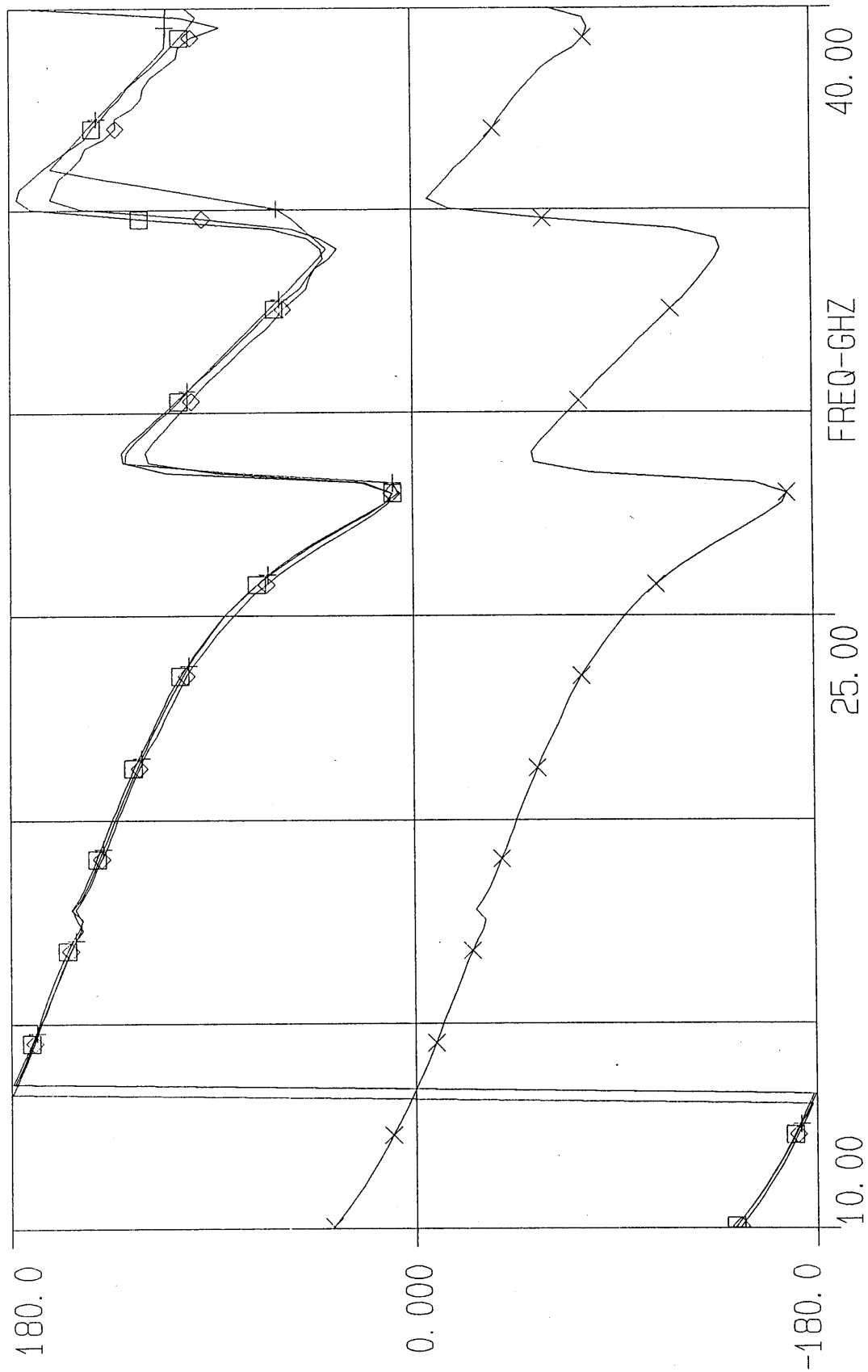
EEsof - Libra - Sun Oct 25 13:09:03 1992 - sh_stubs

□ MAG[S11] + MAG[S11] ◇ MAG[S11] × MAG[S11]
BOE_TRL PMESH TI_TRL TRW_TRL



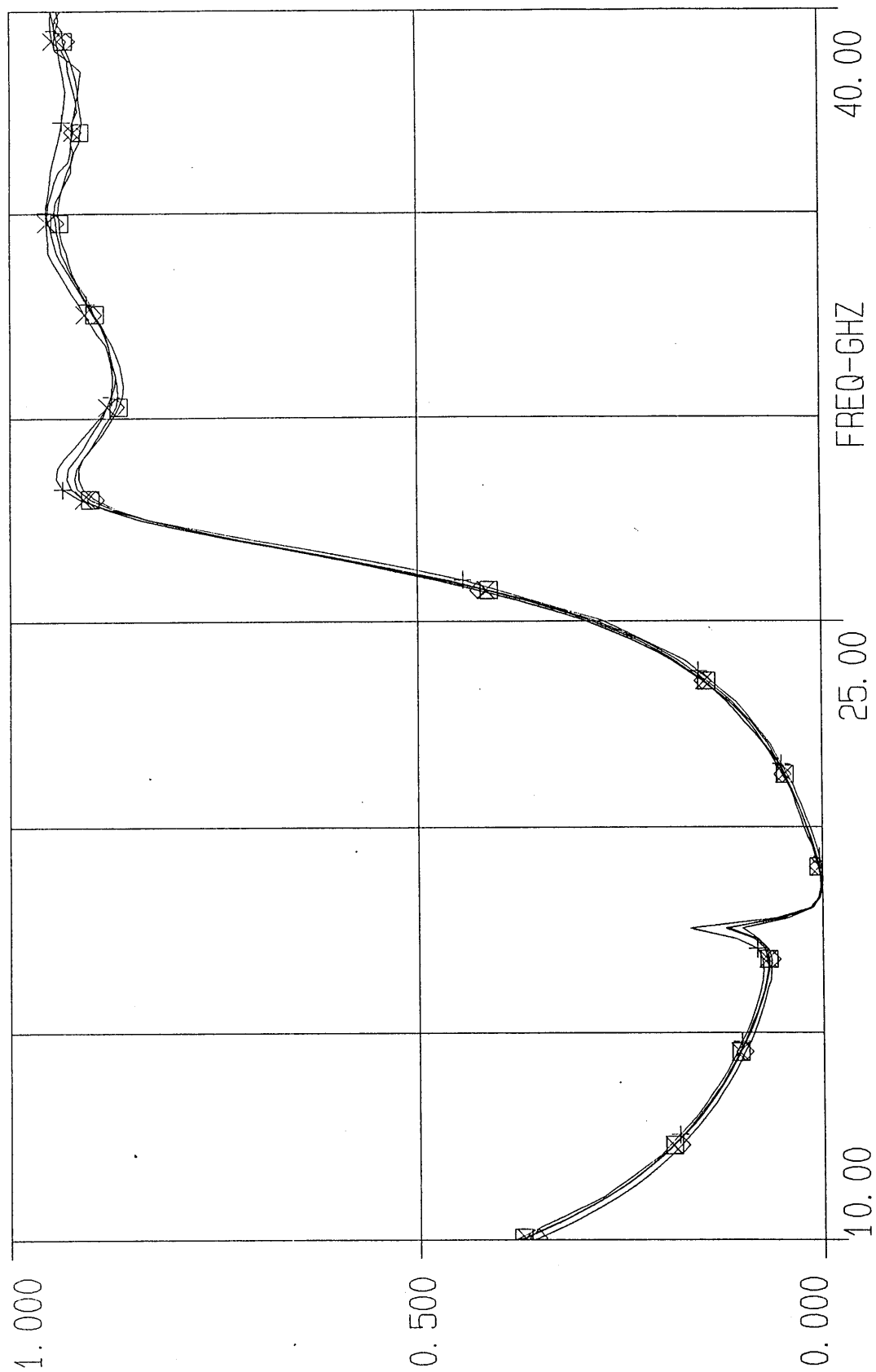
EEsof - Libra - Sun Oct 25 13:09:04 1992 - sh_stubs

□ ANG[S11] + ANG[S11] ◇ ANG[S11] ×
BOE_TRL PMESH TI_TRL TRW_TRL



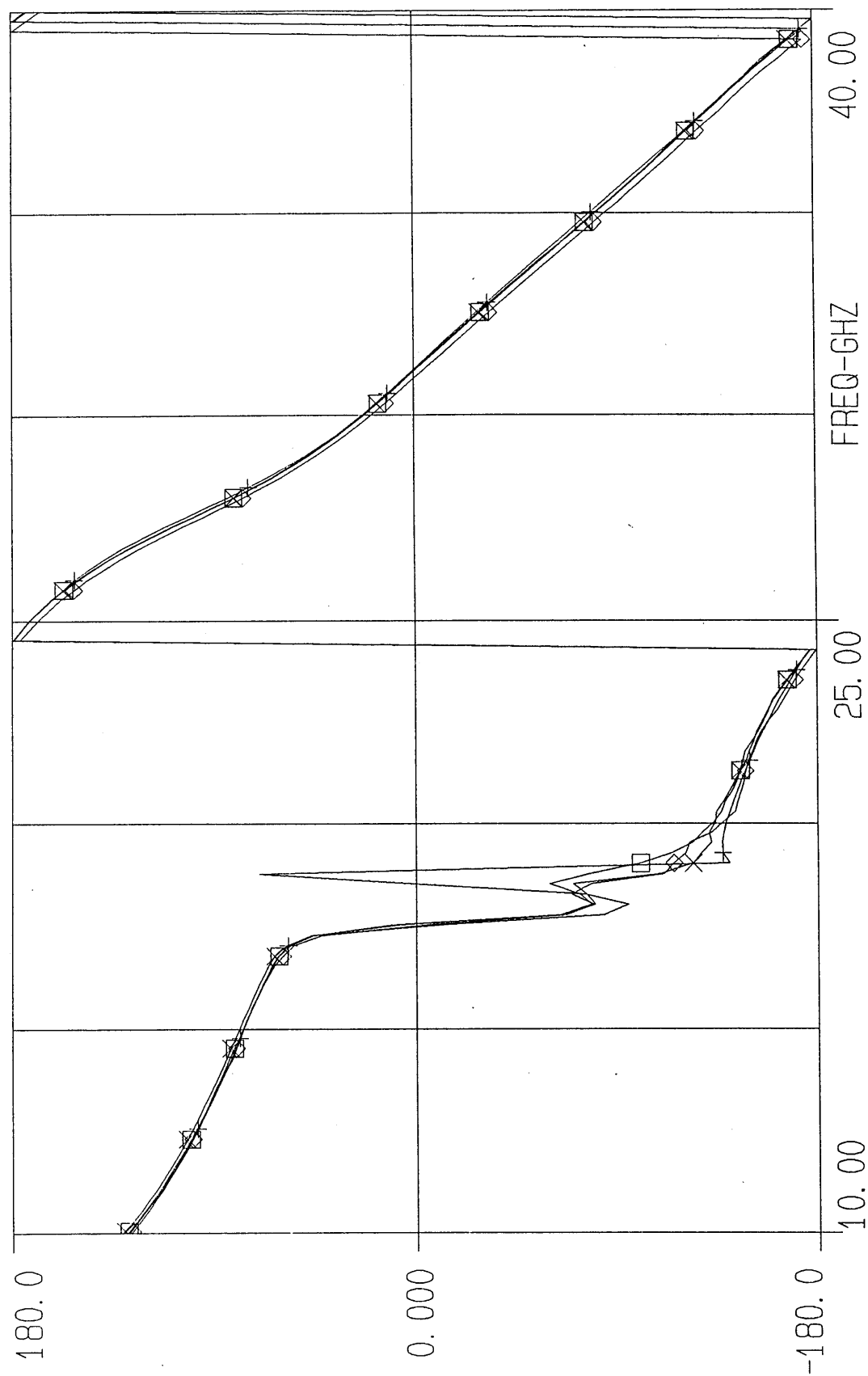
EEsof - Libra - Sun Oct 25 13:09:01 1992 - sh_stubs

□ MAG[S21] + MAG[S21] ◇ MAG[S21] × MAG[S21]
BOE_TRL PMESH TI_TRL TRW_TRL



EEsof - Libra - Sun Oct 25 13:09:02 1992 - sh_stubs

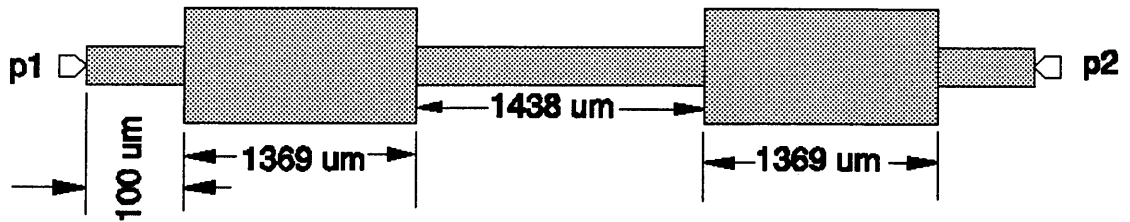
□ ANG[S21] + ANG[S21] × ANG[S21]
BOE_TRL PMESH TI_TRL TRW_TRL



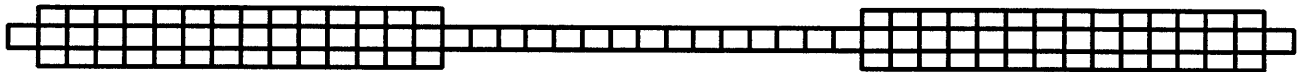
12: Series Stubs

Label: ser_stub

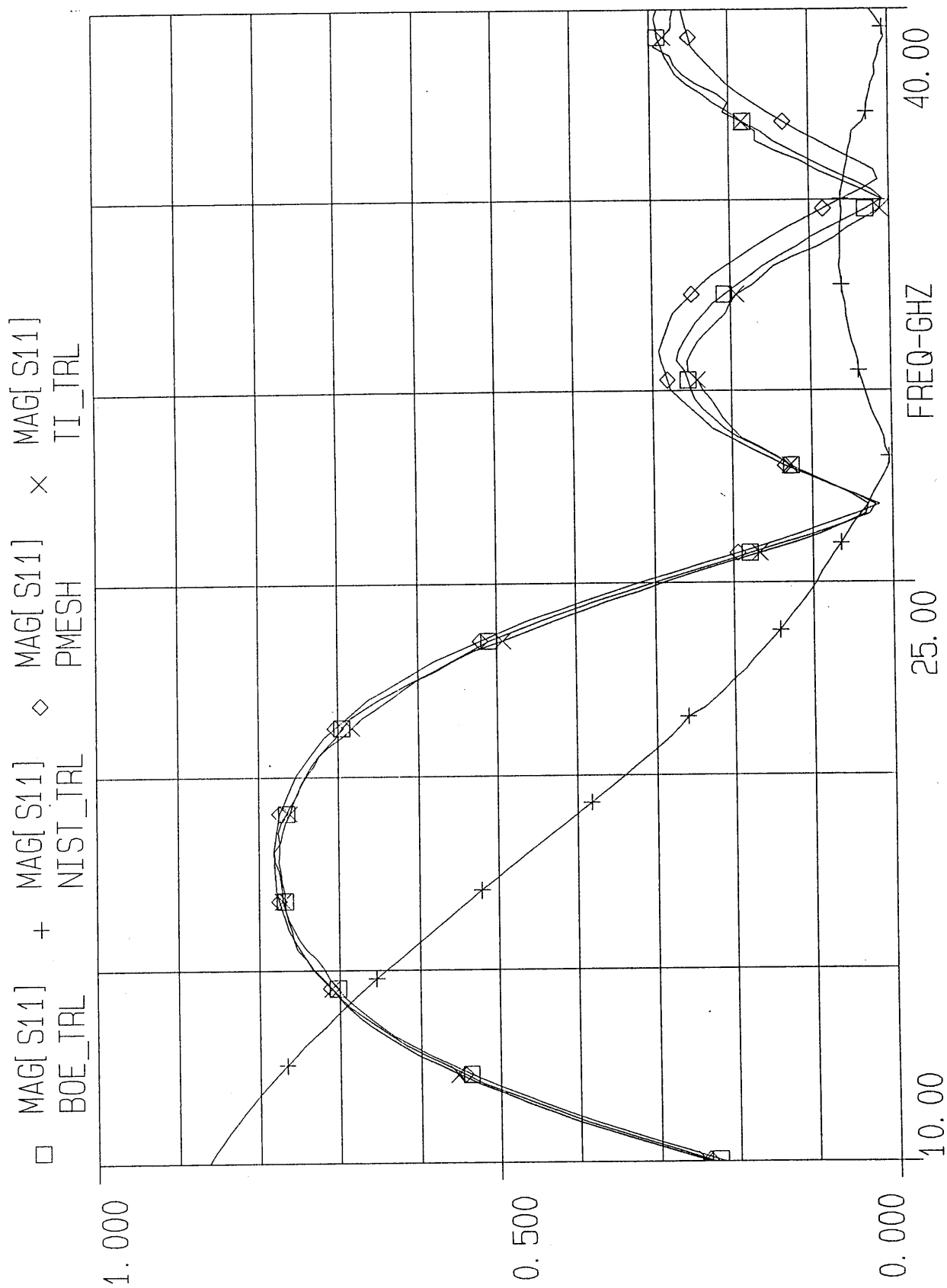
Dimensions:



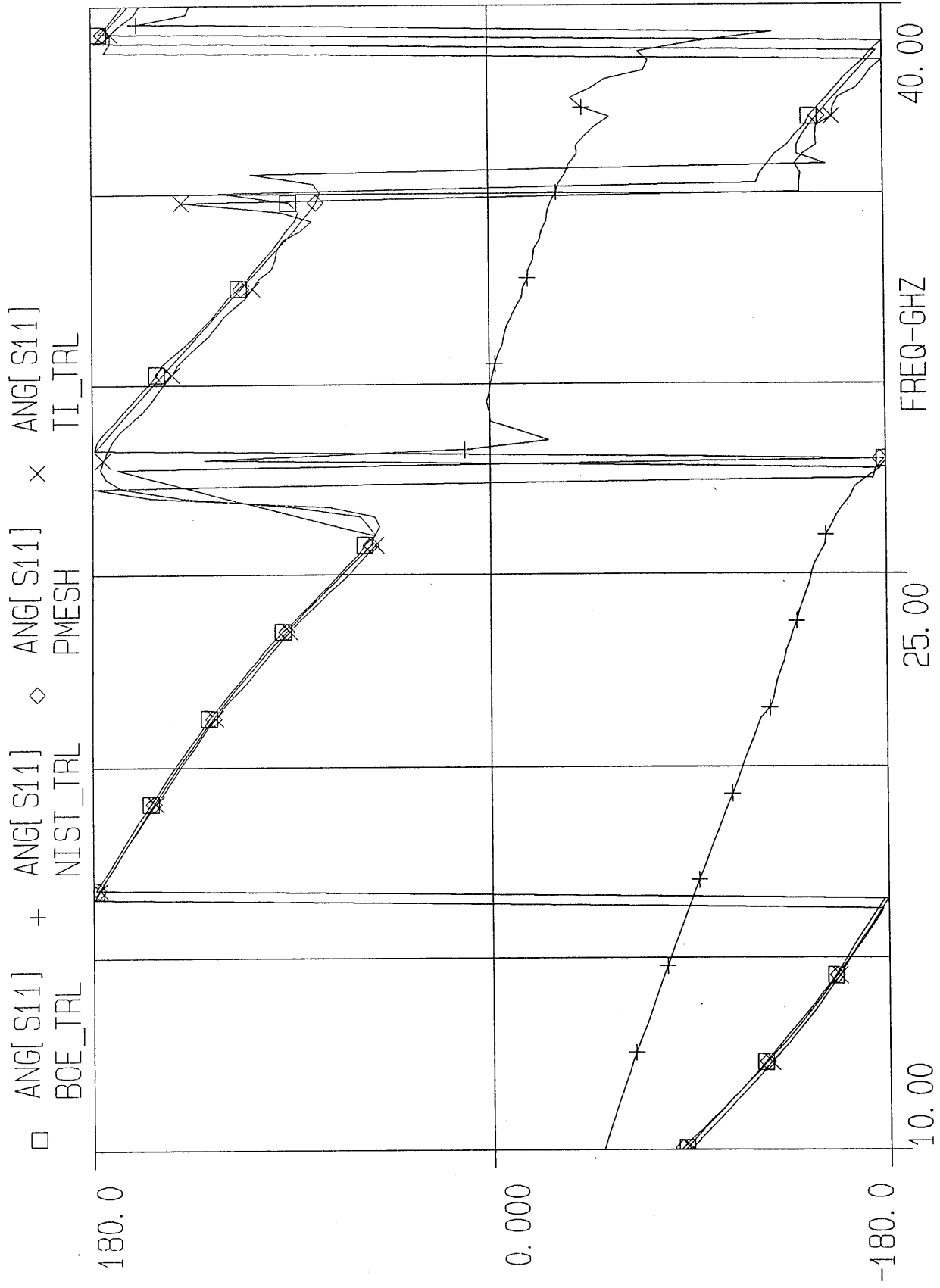
Gridded Geometry:



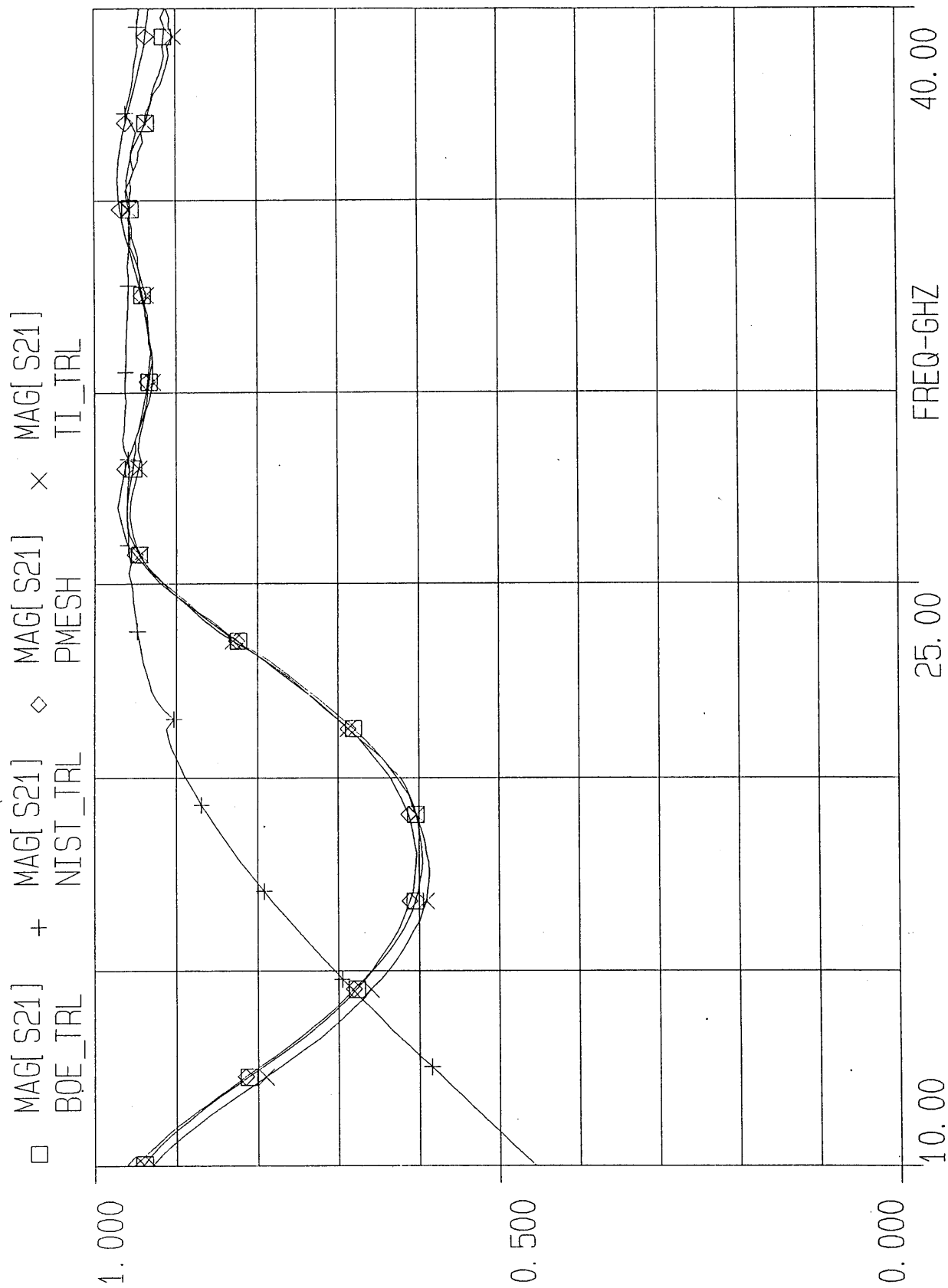
EEsof - Libra - Sun Oct 25 13:15:34 1992 - ser_stub



EEsof - Libra - Sun Oct 25 13:15:34 1992 - ser_stub



EEsof - Libra - Sun Oct 25 13:15:32 1992 - ser_stub



EEsof - Libra - Sun Oct 25 13:15:32 1992 - ser_stub

