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Millimeter waves, Electronic-beam steering, Power combining, Diode Grids Phase-shifter grids, Multiplier grids, Oscillator grids

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We are developing a new approach to millimeter-wave systems based on periodic grids of diodes and transistors, and quasi-optical components like gratings, dielectric slabs, and mirrors. The grids contain large numbers of identical devices, like Schottky diodes, MESFET's, and Gunn diodes that are relatively easy to make with high yield. In addition, the component can function with some failures. Power combining is done in free space, so that the losses associated with corporate feeds are avoided. With

grid technology, it should to be possible to make high-power oscillators with directive beams, high-power multipliers, electronic beam-steerers, and receivers. These should be useful in many millimeter-wave radar and communications systems and as sources for imaging arrays. So far we have been able to demonstrate phase-shifters, multipliers, and oscillators.

ARO 22906.23-EL

# Electronic Beam Steering and Monopulse Receivers for Millimeter Waves

*David Rutledge*
*California Institute of Technology*

Final Report

August 1, 1985 through December 31, 1988

Contract DAAG29-85-K-0184



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## Conferences, Papers, and Abstracts

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"DC and Millimeter-Wave Performance of Watt-Level Barrier-Intrinsic-$N^+$ Diode-Grid Frequency Multiplier Fabricated on III-V Compound Semiconductors," R. J. Hwu, L. P. Sadwick, N. C. Luhmann, Jr., and D. B. Rutledge, Int. Electron Devices Meeting, San Francisco, CA, December 1988.

## PH. D.'S EARNED

Richard Compton is Assistant Professor at Cornell University

Dayalan Kasilingam is at *Ocean Engineering*, a spin-off of JPL that does synthetic-aperture radar analysis.

Wayne Lam is in the millimeter-wave area at TRW

Gabriel Rebeiz is Assistant Professor at the University of Michigan

Wyman Williams has started a company in Pasadena, *MetriWave*, to make a PC-based microwave network analyzer, and has SBIR grants from the Harry Diamond Laboratory and the Jet Propulsion Laboratory.

## CANDIDATES CURRENTLY SUPPORTED FOR THE PH.D. DEGREE

Zorana Popović and Moonil Kim are working on MESFET transistor grids.

Bobby Weikle is working on a monolithic Gunn-diode grid.

## RESEARCH FINDINGS—OVERVIEW

A major problem with millimeter-wave system design is that it is difficult to scale down conventional microwave systems based on waveguides and tubes. Recent developments in gallium-arsenide technology have stimulated a renewed attack on these problems, and the Department of Defense is sponsoring the development of large millimeter-wave phased-arrays through the MIMIC program. These systems are composed of sub-array building blocks that include a housing structure, a feed network, and a series of hybrid components that are wire-bonded to gallium-arsenide chips. The chips include monolithic circuits like phase shifters, low-noise and buffer amplifiers, digital control circuits, radiating elements, and their inter-connecting transmission lines. However, there are problems with this approach. Processing difficulties and defects in the wafer reduce the yield of these circuits. In addition, since each radiating element requires individual control circuits, amplifiers, and phase shifters, these systems are quite complex and use a lot of power. In this contract, we have developed a new approach to millimeter-wave systems based on periodic grids of diodes and transistors and quasi-optical components like gratings, dielectric slabs, and mirrors. Much of the work has been done in collaboration with Neville Luhmann's group at UCLA.

The grid technology that we developing at Caltech and UCLA has several advantages. The complex RF control lines are replaced by simple low-frequency wires. The grids contain large numbers of identical devices, like Schottky diodes, MESFET's, Gunn diodes, that are much easier to make with high yield than complex circuits that contain many elements. In addition, the grids appear to function even when many of the devices are not working. Power combining is done in free space, so that the losses associated with corporate feeds are avoided. Passive circuit functions like filters, couplers, and shorts are implemented with quasi-optical dielectric slabs and mirrors, which typically have much better performance at millimeter wavelengths than their microstrip counterparts. With grid technology, it should to be possible to make high-power oscillators with directive beams, high-power multipliers, electronic beam-steerers, and receivers. These should be useful in many millimeter-wave radar and communications systems and as sources for imaging arrays. So far we have been able to demonstrate phase-shifters, multipliers, and oscillators. The key papers published under this contract that describe these new components are:


[1] W. W. Lam, C. F. Jou, H. Z. Chen, K. S. Stolt, N. S. Luhmann, D. B. Rutledge, "Millimeter-Wave Diode-Grid Phase-Shifters," *IEEE Transactions on Microwave Theory and Techniques 36*, pp. 902-907, 1988.

[2] Christina F. Jou, Wayne W. Lam, Howard Z. Chen, Kjell S. Stolt, Neville C. Luhmann, Jr., and David B. Rutledge, "Millimeter-wave monolithic Schottky diode-grid frequency doubler," *IEEE Trans. on Microwave Theory and Tech. 36*, pp. 1507–1514, 1988.

[3] Zorana B. Popović, Moonil Kim, and David B. Rutledge, "Grid oscillators," *International Journal of Infrared and Millimeter Waves 9*, pp. 647–654, 1988.

## RECENT RESEARCH FINDINGS—SABBATICAL IN JAPAN

I spent much of the last six months in Koji Mizuno's Laboratory at Tohoku University in Sendai, Japan. There I helped supervise two graduate students: Morishige Hieda, who built a Gunn-diode oscillator grid with 9 locked diodes, and Kazuhiro Uehara, who is developing lens-coupled imaging arrays based on Yagi-Uda antennas. This work is summarized in two papers that were given at the Infrared and Millimeter Waves Conference in Honolulu, and these abstracts are attached.

## RECENT RESEARCH FINDINGS—OSCILLATOR GRIDS

The goal of this research is to develop a high power, cheap, reliable solid state source in the millimeter-wave region. The main motivations are compactness and the fact that such a source can be made monolithically with the other parts of the system (e.g. mixer diodes). We make such a source by quasi-optical power combining. We would like to make a combiner which allows a very large number, say a thousand, individual oscillators, but in such a way that they share the same biasing, coupling and matching circuit. We do that by loading a two-dimensional grid with active devices. The idea is that as the grid becomes several wavelengths across, and if the devices are close compared to a wavelength, the whole grid looks like a continuous active sheet. The wave that is radiate is a plane wave, which is important for applications such as radar and communication transmitters.

A model of such an oscillator grid in X-band was described in [3]. The metal grid was on top of a quarter-dielectric-wavelength thick substrate and consisted of 25 Fujitsu MESFETs. It exhibited locking and power-combining at 9.7 GHz. The maximum measured ERP (effective radiated power with respect to an isotropic source) was 37 W with a directivity of 16 dB. The radiation pattern agreed well with a theoretical pattern obtained using reciprocity. However, this setup is hard to analyze from the point of view of the device. Finding the impedance that the device is looking into is not an easy job for several reasons. The substrate is thick, so substrate modes affect the mutual coupling. RF currents are flowing in all directions, which makes the coupling between the currents and fields hard to describe.

We have developed a new grid structure which enables us to predict the impedance that the leads of transistor see. It is shown on Fig. 1. The MESFETs are soldered onto metal bars. The bars provide isolation between the drain and gate, efficient heat-sinking of the source and act as a semitransparent reflector. We have developed a theory which gives an equivalent circuit model for a unit cell of the grid. The unit cell is defined by boundary conditions at the symmetry lines of an infinite grid with all gate and drain currents in phase, as shown in Fig. 2. On the $y$-directed symmetry lines, the tangential magnetic fields cancel, so we can define the boundary conditions by placing magnetic walls. The unit cell looks like a transversal cross section of a rectangular waveguide with electric walls in the $x$ direction and magnetic ones in the $y$ direction.

The induced emf method was used to find the impedance seen by the leeds in the unit cell. This method is an application of Pointing's theorem, and was developed by Carter in the early thirties. We first find the dyadic Green's function for given boundary conditions, and assume a current distribution to find the fields and then the reactive power, from which the impedance is found. All these modes that have an imaginary impedance are evanescent, and there will be one mode that will propagate and have a real impedance, which can be modeled as a section of a transmission-line. An electric current gives the evanescent electric field and an equivalent inductive reactance. The dual problem is a magnetic current which gives the evanescent magnetic field and a capacitive reactance.

The unit cell has more than one waveguide, and mutual inductances and capacitances will also exist. Odd and even modes of the currents and voltages were used to find the self and mutual inductances and capacitances, as shown on Fig. 3. Looking from the side, the leads of the transistor are current strips that excite fields in the waveguides formed by the metal plates. These fields can be represented as voltages between the metal walls. We can separately look at odd and even modes by looking at currents and voltages that are in the same or opposite direction. Let us first look at the currents.

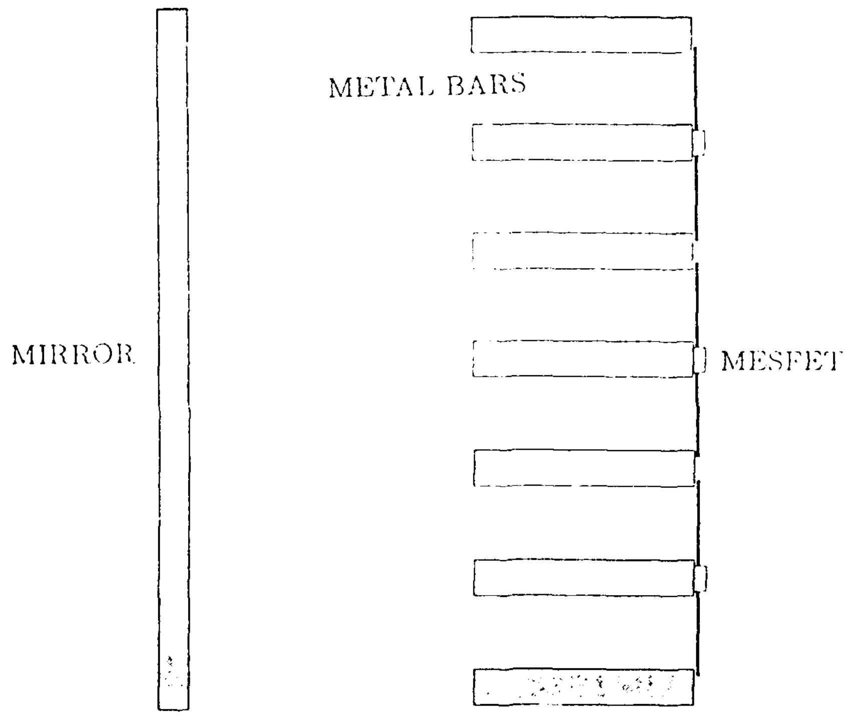


**Figure 1** New grid configuration.

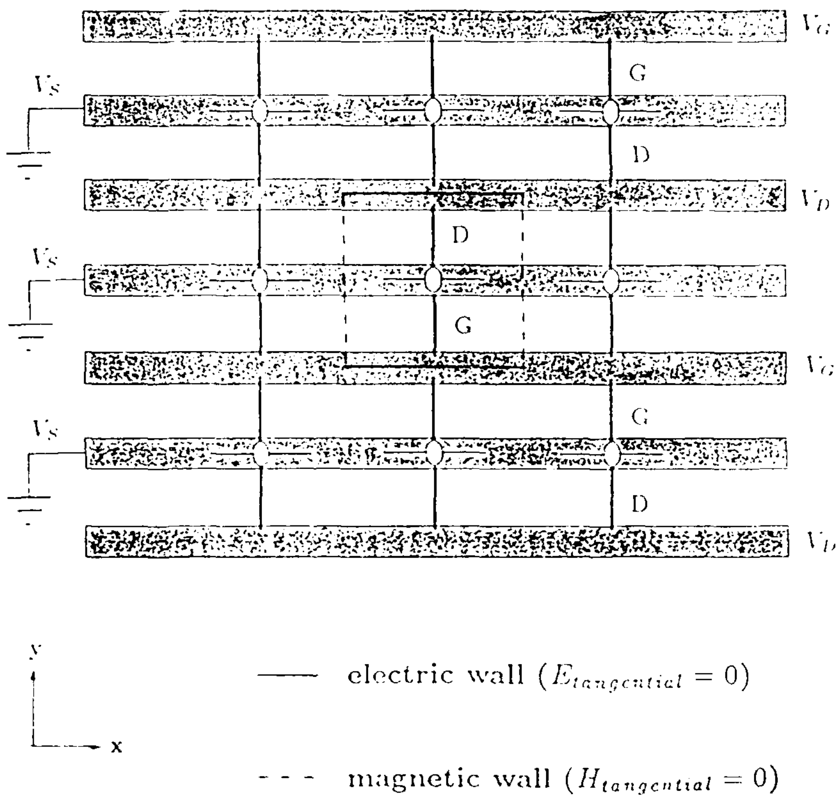


**Figure 2** Symmetry defines a unit cell with electric and magnetic walls.

shown on Fig. 4. The center metal plate is grounded, so in the first case, the currents are opposite, and their magnetic fields add at the symmetry line (they both go into the plane), while there is no tangential electric field, so we can put an electric wall in the middle. In the case when they are in phase, the tangential magnetic field on the symmetry line is zero, so we can put a magnetic wall there. Similar reasoning holds for the electric fields, and we can again put a magnetic and electric wall in the middle and keep the boundary conditions satisfied. From Fig. 4, in one case the equivalent inductance will be the difference, and in the other case the sum of the self and mutual inductances of the small waveguide, and we can obtain L and M directly. Similarly, in one case the total capacitance is the sum of the self capacitance and twice the mutual capacitance. In the second case, it is just equal to the self capacitance, since the voltages are such that due to symmetry no extra charge is formed.

Now we have the complete circuit model for each transistor, with all the parasitics. For the dimensions convenient for making the grid with the Fujitsu transistors, the values are found to be: $R_{TEM} = 113\Omega$, $X_L = 95\Omega$, $X_M = 1\Omega$, $X_C = 200\Omega$, $X_{Cm} = -400\Omega$.

We now use PUFF, a CAD program developed by Rick Compton. Although PUFF is

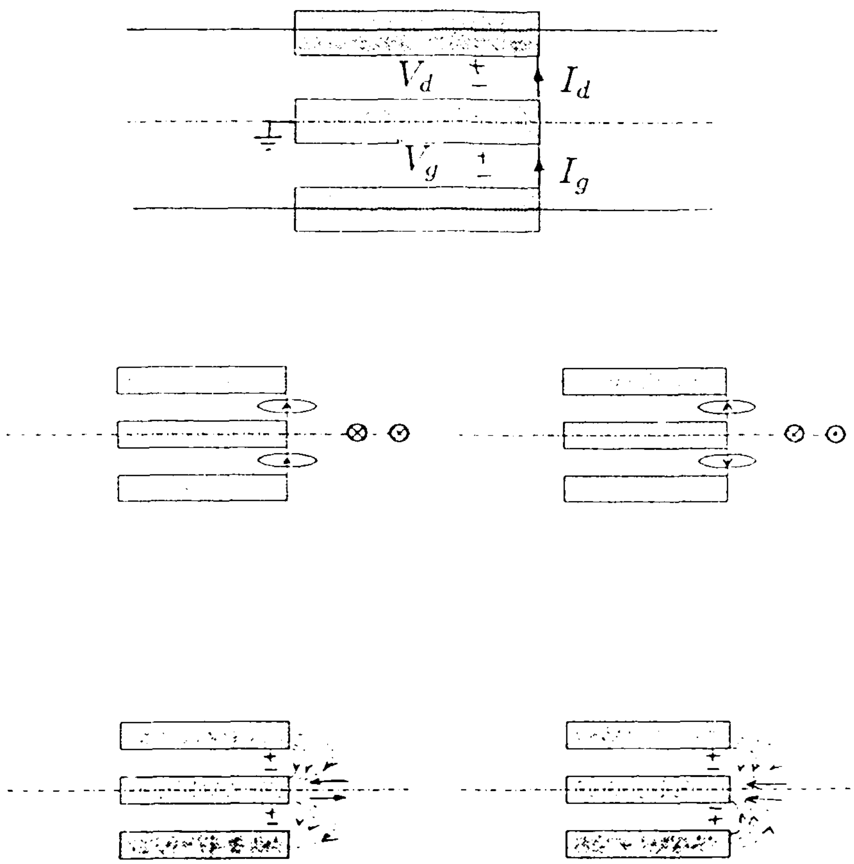


**Figure 3** Odd and even current and voltage modes define boundary conditions

intended for analysis of microstrip circuits, by proper normalization any transmission-line circuit with lumped elements can be analyzed. The loop on the Smith chart is outside the $r = 1$ circuit and spirals in the counterclockwise direction (Fig. 6) indicating an instability. We analyse the oscillator by looking into the oscillator circuit from an external port terminated by a matched load. The oscillation condition is that the product of the reflection coefficient of the transistor oscillator $s_{11}$ and the reflection coefficient of the load $s_L$ is 1. As the oscillations build up $s_{11}$ loops clockwise around the point $1/s_L$, until the transistor saturates. Since $s_L$ is that of a matched load, $1/s_L$ is a point at infinity. How can the clockwise loop inclose a point at infinity? The solution is to make a counterclockwise loop. The Smith chart is a bilinear transformation. If both loops are clockwise, the interior maps into the interior. If the direction of the loop changes, the interior maps to the exterior, so the point at infinity can be included. To demonstrate this, we simulated the saturation of the transistor by decreasing the $s_{21}$ (transmission) parameter. As the transistor goes into saturation, the counterclockwise circle becomes larger, and after it passes the point at infinity, it starts spiraling in the clockwise direction, indicating no more oscillation, as shown in Fig. 7.

We are presently building a 36 transistor grid. We plan to build larger grids to investigate the radiated power, directivity and noise versus the number of devices.

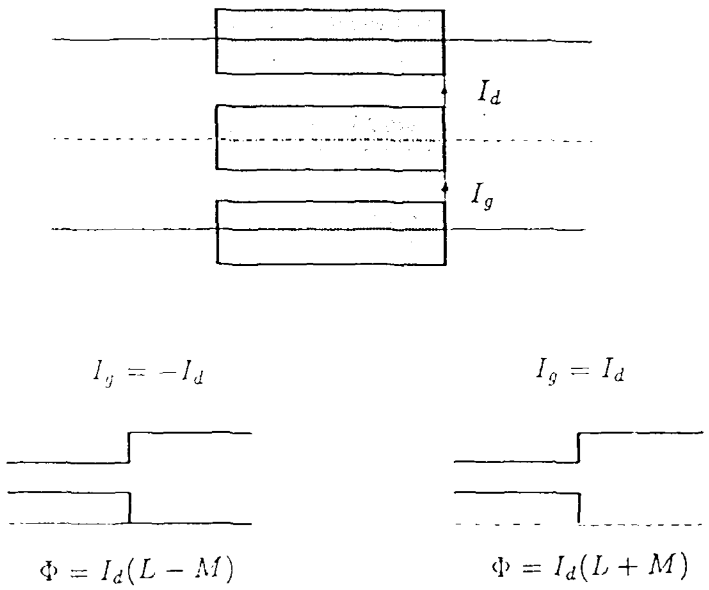


**Figure 4** Finding self and mutual inductance using odd and even current modes.

If the linear dimension of the grid is $r$, the power should be proportional to $r^2$, the directivity to $r^2$, and the ERP with respect to an isotropic source to $r^4$. This means that we should be able to get 10 kW ERP from one hundred transistors. The noise power should be proportional to $r^2$ and the signal to noise ratio to $r^2$. We are setting up a phase and amplitude noise measurement. We are also interested in investigating the reliability, namely what happens if a few devices across the grid fail. Finally, the design of a monolithic Gunn-diode grid oscillator is in progress.

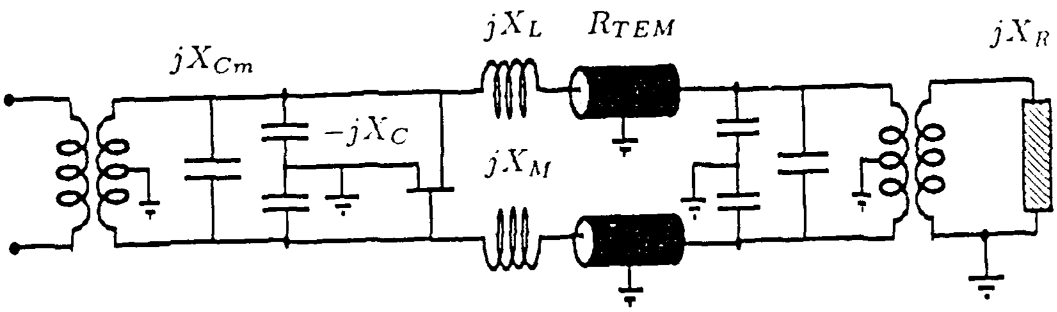


**Figure 5** Equivalent circuit of the unit cell.

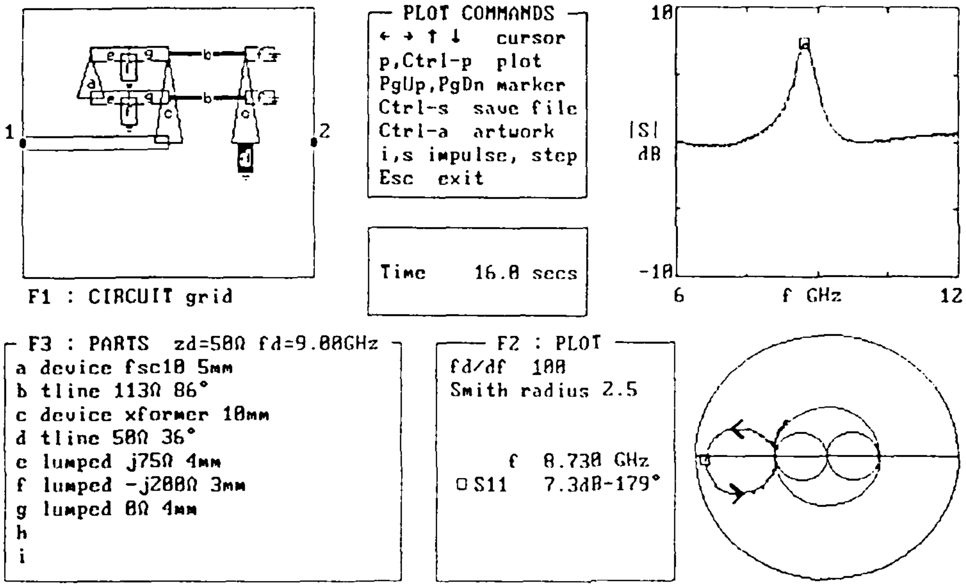


Figure 6 PUFF simulation of transistor oscillator.

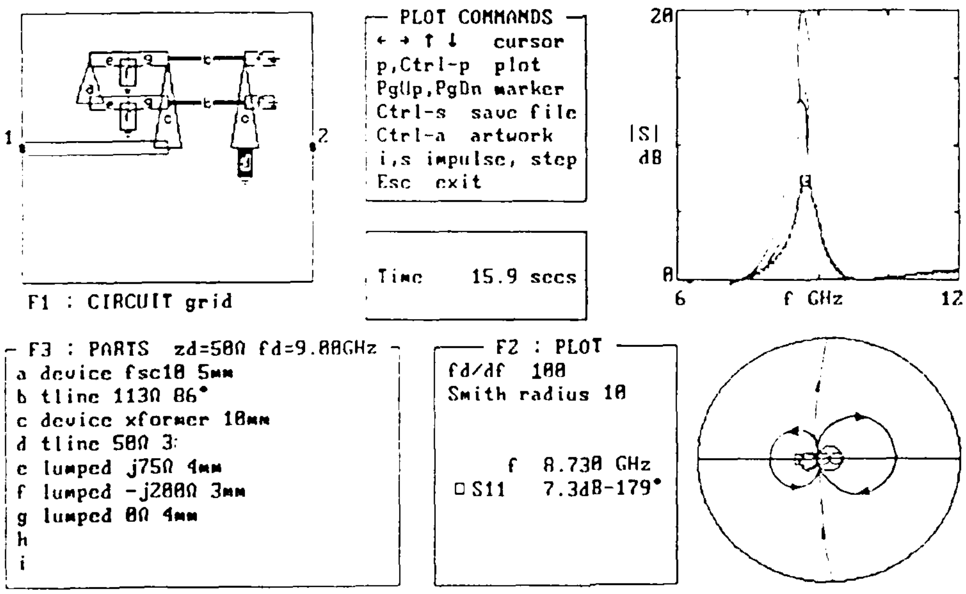


Figure 7 PUFF simulation of transistor saturation.