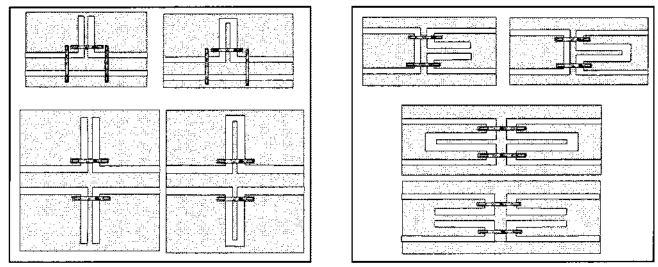
Size-Reduction Techniques for CPW and ACPS Structures

Khelifa Hettak, Tony Laneve, and Malcolm G. Stubbs

***Abstract*—In coplanar-waveguide technology, there is a possibility of locating shunt and series matching stubs inside the center conductor of the transmission line. This principle can be used to reduce of the dimensions of microwave components such as monolithic microwave integrated circuits. This paper discusses the concept and presents the design of a reduced-size Wilkinson divider based on the realization of short-circuit series stubs in the signal conductor of an asymmetric coplanar stripline.**

***Index Terms*—Coplanar stripline, coplanar waveguide, couplers, MMICs, passive circuits.**



(a) (b)

Fig. 1. Comparison between the layout of: (a) conventional CPW shunt stubs and (b) shunt stubs patterned in the center conductor.

I. INTRODUCTION

THE recent interest in new wireless applications, such as local multipoint communication system (LMCS)/local multipoint distribution system (LMDS), is creating a demand for monolithic microwave integrated circuits (MMICs) at high frequencies. Chip size is one of the key considerations in MMIC design and, for this reason, lumped elements have been very popular below 20 GHz. At higher frequencies, however, lumped element losses, self resonance effects, and parasitics, in general, become significant, and a distributed approach becomes more attractive, especially since the wavelength is less of a factor. In distributed element-based MMICs, the microstrip is the most common transmission-line approach. However, the coplanar waveguide (CPW) has many features such as low dispersion, easy integration of shunt active and passive elements, the ability to easily realize short-circuit elements, absence of via holes, etc., which make it an attractive technology to the MMIC designer, particularly at millimeter-wave frequencies. A variant of the CPW, the asymmetric coplanar waveguide (ACPS) is also attractive for MMIC applications since the single ground plane does not require air bridges to suppress higher order modes at discontinuities.

A CPW offers the ability to realize series, as well as shunt matching elements; this extra degree of freedom offering increased design flexibility over microstrip. Use of both series and shunt CPW matching stubs can lead to novel passive structures that allow significant size reduction to be achieved. Series matching stubs are also possible in an ACPS, but to the authors' knowledge, shunt ACPS elements have not been demonstrated and a lack of such elements will limit the application of an ACPS.

This paper presents concepts that can lead to a reduction in the overall size of MMIC chips. First, the possibility of incorporating shunt matching elements in the center conductor of a CPW is presented. Second, examples of new shunt ACPS elements are introduced and techniques for reducing their lengths are also shown. Finally, a reduced-size Wilkinson divider in an ACPS is shown to illustrate how effectively such techniques can be used to reduce the size of MMIC components.

II. CENTER CONDUCTOR SHUNT STUBS IN A CPW

It has previously been shown that CPW series stubs can be realized in both the "inner" or "outer" conductors of a CPW line [1], [2]. CPW shunt stubs, on the other hand, are typically connected to the inner conductor, but located in the ground plane. It is possible, however, to also print them in the inner conductor and Fig. 1 shows these new types of CPW shunt stubs along with their analogous stubs printed conventionally in the ground plane. To establish the appropriate fields, a portion of the ground plane is introduced across the CPW in the form of a thin strip. Inner conductor continuity is maintained using air-bridge interconnects across the strip, and stubs to ground are formed within the center conductor using the new local ground point.

In comparison with conventional CPW shunt stubs, the following advantages are obtained from the use of the new shunt stubs:

1) compactness, thereby providing low loss;
2) reduction in the lateral footprint of the circuit;
3) reduction in the number of air bridges in the case of asymmetric CPW shunt stubs;
4) transverse symmetry around the center conductor.

The location of the stubs within the center conductor also leads to greater field confinement and, thus, lower radiation loss.

Manuscript received February 28, 2001.

K. Hettak and M. G. Stubbs are with the Communications Research Centre, Ottawa, ON, Canada K2H 8S2.

T. Laneve was with the Communications Research Centre, Ottawa, ON, Canada K2H 8S2. He is now with the Monolithic Microwave Integrated Circuit Design Group, Nortel Networks Optical Components Corporation, Ottawa, ON, Canada K2H 8E9.

Publisher Item Identifier S 0018-9480(01)09384-X.

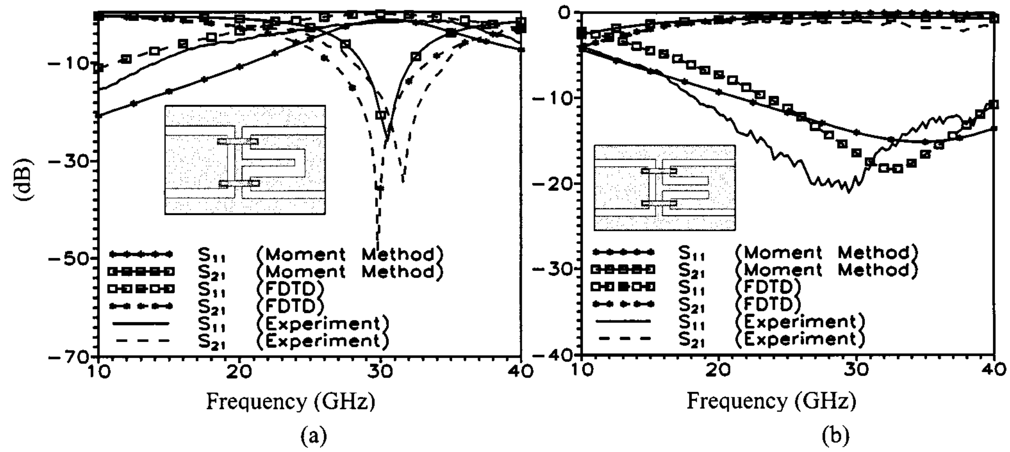


Fig. 2. Experimental and theoretical results for center-conductor versions of ACPS, open-circuit, and short-circuit CPW shunt stubs.

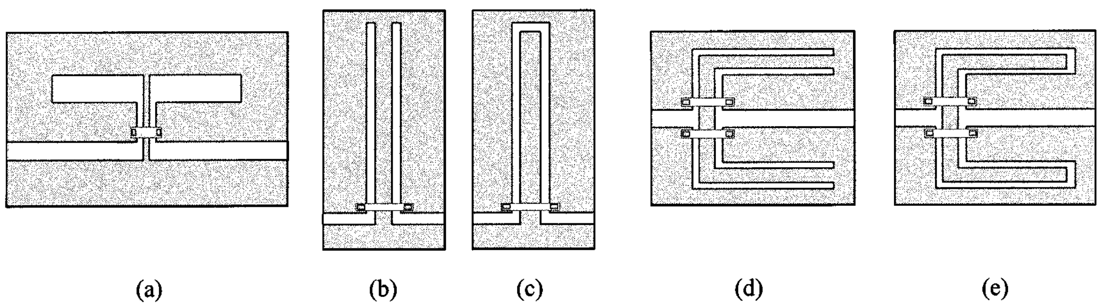


Fig. 3. Examples of ACPS shunt stubs. (a) Short-circuit stub: ACPS format. (b) Short-circuit stub: CPW format. (c) Open-circuit stub: CPW format. (d) Short-circuit double stub: CPW format. (e) Open-circuit double stub: CPW format.

Furthermore, the symmetry around the center conductor indicates that the parasitic coupled slotline mode should not theoretically be excited in these structures. (This contrasts with the conventional asymmetric shunt stub in which two transverse air bridges must be used in addition to the longitudinal air bridge to prevent the coupled slotline mode from being excited.)

To show the potential of the center-conductor-based CPW shunt stubs, several examples have been fabricated. Fig. 2 shows the measured S-parameters of asymmetric CPW shunt stubs along with theoretical results obtained using two different techniques: the integral-equation technique solved with the moment method and complex images and the finite-difference time-domain (FDTD) method. These circuits are designed near $f_o =$ 30 GHz and implemented on high dielectric-constant substrate ($\varepsilon r = 9.9$ and $h = 0.254$ mm). The good agreement between experimental and theoretical results shows that the stubs work well in the millimeter-wave region. Dielectric and conductor losses are neglected in the theoretical analyses and results in the differences between theoretical and experimental resonance frequencies.

III. ACPS Shunt Stubs

Coplanar stripline components such as spur slots, steps, and T-junctions have been investigated and modeled [3], but no attention has been paid to the realization of shunt ACPS elements. Fig. 3 shows examples of ACPS shunt stubs designed to operate around 30 GHz. Two forms of shunt stub are possible depending upon whether they are derived from ACPS or CPW transmission lines. A short-circuit stub made in the form of an ACPS line is illustrated in Fig. 3(a) and a short-circuit stub made in the form of a CPW line is shown in Fig. 3(b). Fig. 3(c) shows an example of an open-circuit ACPS shunt stub in a CPW form. Notice that air bridges are used to maintain ACPS continuity along the main transmission line. Selection of the type of stub determines the impedance ranges that can be achieved, the ACPS form allowing impedances in the 50-150-Ω range and the CPW form allowing lower impedances to be realized (i.e., 30-80-Ω range). For even lower shunt impedances, two stubs of the CPW form can be used in parallel, as shown in Figs. 3(d) and 3(e).

Experimental and theoretical results achieved around 30 GHz for both forms of short-circuit stub are plotted in Fig. 4. Excellent agreement was achieved in the case of the CPW form of ACPS shunt stub, but a frequency offset was observed in the case of the ACPS form. It can be seen that a shunt stub of the type shown in Fig. 3(a) acts like a short circuit since it produces a good match around 30 GHz where the stub length is $\lambda/4$. Similarly, the results show that the stub shown in Fig. 3(c) acts like an open circuit.

IV. Center-Conductor Stubs for Size Reduction

A useful way of reducing the length of $\lambda/4$ transmission lines is to load each end with a shunt capacitance or open-circuit shunt stub. To compensate for the increased capacitance, the Z_o of the shortened transmission line is increased. Length reduction can also be achieved by loading each end with a series inductance (short-circuit series stub) and reducing the Z_o in order to com-

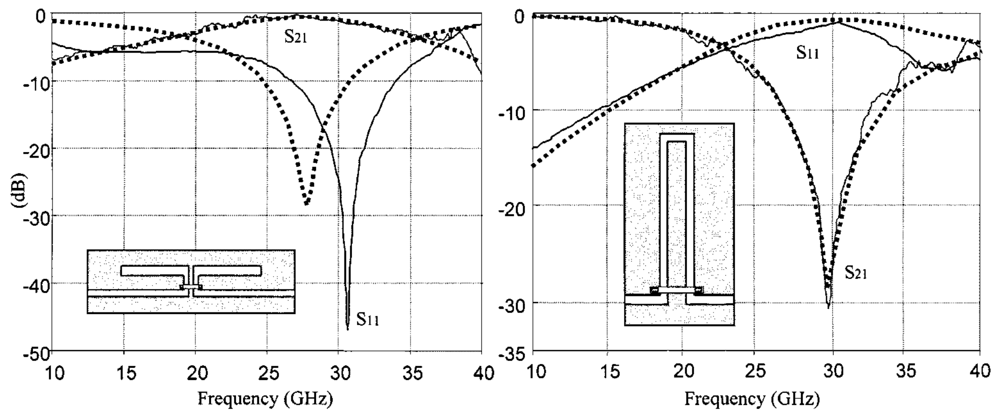


Fig. 4. Theoretical and experimental results for a short-circuit stub (ACPS format) and an open-circuit stub (CPW format).

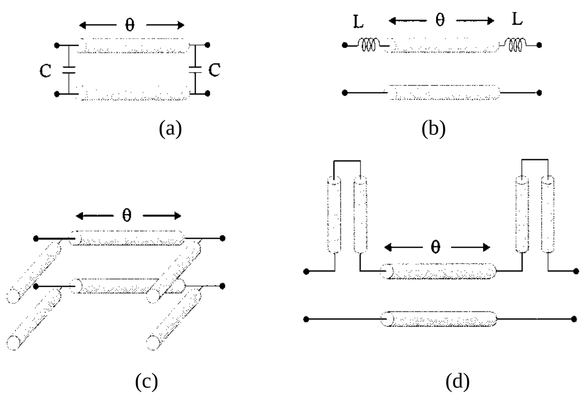


Fig. 5. Shunt and series loaded transmission lines used to represent the behavior of $\lambda/4$ transmission lines (note: $\theta < \lambda/4$).

pensate for the increased inductance (Fig. 5). While the former can be easily realized in microstrip, the latter can only be realized if lumped spiral inductors are used. Unfortunately, these elements are rarely used at high frequencies because they are inherently lossy and have low resonant frequencies. Series stubs are very easily made in a CPW, however, and can be positioned in the center conductor in a similar way to that of the shunt stubs discussed above.

In order to determine the value of series inductance loading each end of the line, we equate the $ABCD$ matrix of a $\lambda/4$ transmission line with characteristic impedance $Z_{\rm o}$ to a shorter loaded transmission line of length θ_1 and impedance $Z_{\rm o1}$ as follows:

$$\sin(\theta_1) = \frac{Z_{\rm o1}}{Z_{\rm o}} \quad L = \frac{Z_{\rm o1}}{\omega \cdot \tan(\theta_1)}. \tag{1}$$

If the series inductances are represented by short-circuit series stubs of length $\theta_{\rm s}$, and impedance $Z_{\rm os}$, then it can be shown that

$$\tan(\theta_1) \cdot \tan(\theta_{\rm s}) = \frac{Z_{\rm o1}}{Z_{\rm os}}. \tag{2}$$

From (1), it is seen that the line can be reduced to less than 90° if $Z_{\rm o1}$ of the shortened line is less than the $Z_{\rm o}$ of the $\lambda/4$ line.

V. A Reduced-Size Wilkinson Divider

Using the above equations, a reduced-size Wilkinson divider was designed in an ACPS using a series stub structure. The

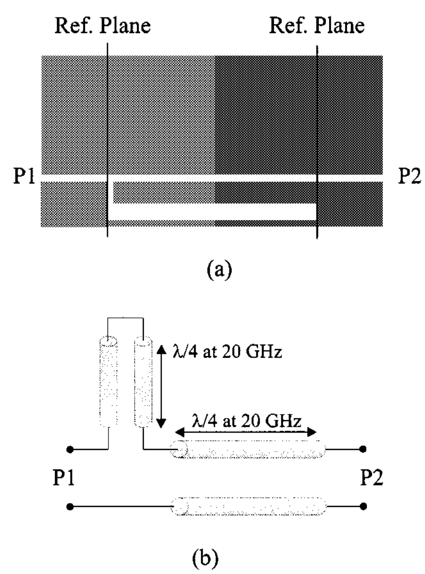


Fig. 6. (a) ACPS short-circuit series stub. (b) Ideal equivalent circuit.

ACPS was chosen over a CPW because it avoided the problem of having a central ground area between the two arms of the divider. Fig. 6(a) shows the physical layout of an ACPS series stub embedded in the signal conductor of the main ACPS line, while the ideal lossless transmission-line equivalent circuit is indicated in Fig. 6(b). From Fig. 7, it can be seen that the structure has the characteristics of a short-circuit series stubs in series with a transmission line.

The complete Wilkinson divider is shown in Fig. 8. Two ACPS short circuit series stubs can be seen in each arm of the coupler, reducing the length and $Z_{\rm o}$ of the two arms from the standard 90° and 70.7-Ω impedance to approximately 60° with 61-Ω impedance. Finite-ground CPW feed lines are used at each of the ports. A size reduction of approximately 30% was achieved.

VI. Fabrication and Results

The reduced size divider was fabricated using an in-house miniature hybrid microwave integrated circuit (MIC) process at the Communications Research Centre (CRC), Ottawa, ON, Canada. The metal traces are gold and the resistor is TiW. The

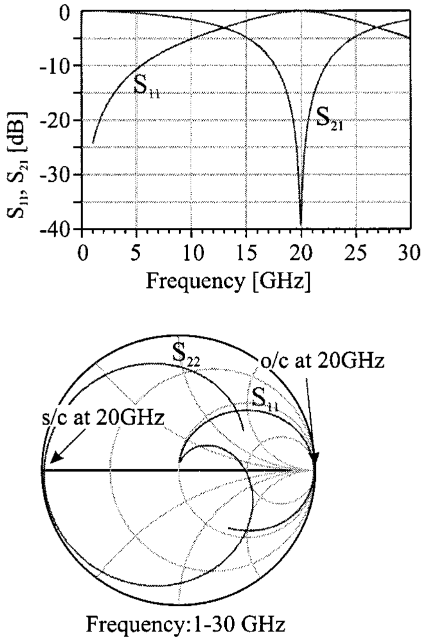


Fig. 7. Simulated performance of ACPS short-circuit series stub.

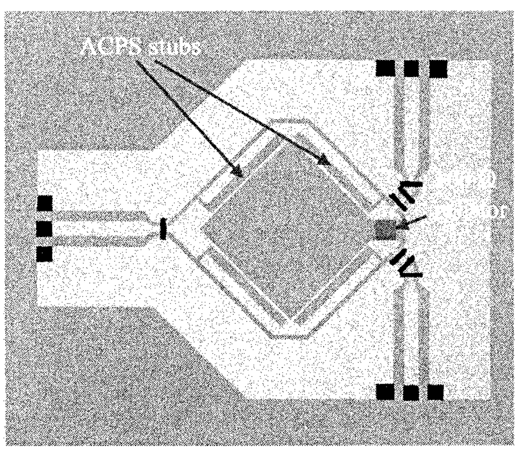


Fig. 8. Reduced-size Wilkinson divider. The metallized areas are 1.48 × 1.13 mm in size.

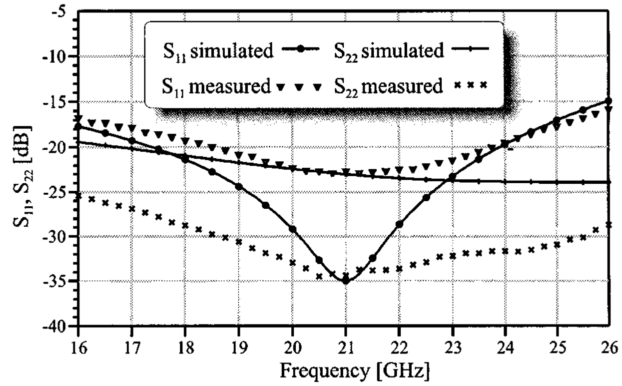


Fig. 9. Simulated and measured return losses.

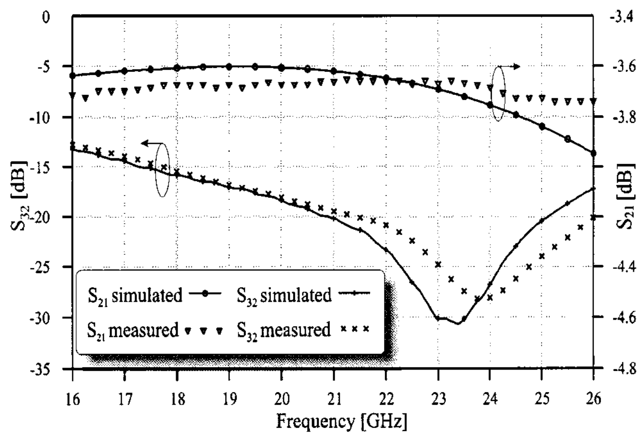


Fig. 10. Simulated and measured coupling and isolation.

substrate was high-resistivity silicon ($\rho > 10,000\Omega \cdot$ cm) with a thickness of 400 μm. In order to facilitate on-wafer probing, a second divider layout was made having one of the output ports directly connected to an integrated 50-Ω resistor. A third layout was configured to allow measurement of the isolation performance.

The circuit was measured using a Wiltron 360 vector network analyzer (VNA) and ground–signal–ground (G–S–G) probes. The thru-reflection-line (TRL) calibration technique was employed and CPW standards were printed on-wafer for this purpose.

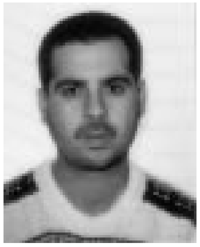
The simulated and measured results are shown in Figs. 9 and 10. At midband, the return loss and isolation is about 20 dB, while the insertion loss is approximately 0.7 dB. Reasonably good agreement between simulation and measurement was obtained. Note that, for the isolation measurement, the input was terminated with a coaxial 50-Ω load connected to the G–S–G probe. As a result, the input was not perfectly matched. To account for this in the simulation, the reflection coefficient of the probe and 50-Ω load was measured and included in the simulation

VII. Conclusions

The patterning of series and shunt stubs in the center conductor of CPW lines can offer advantages over the conventional approach of locating them in the ground plane. The new concept of ACPS shunt stubs has been introduced and an example of how center-conductor-based stubs can be used to achieve size reduction has been presented in the form of a Wilkinson divider. A 30% size reduction has been achieved

References

[1] T. M. Weller and L. P. Katehi, “Miniature stub and filter designs using the microshield transmission line,” in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1995, pp. 675–678.
[2] N. Dib *et al.*, “Theoretical and experimental characterization of coplanar waveguide discontinuities for filter applications,” *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 873–882, May 1991.
[3] K. Goverdhanam, R. N. Simons, and L. P. Katehi, “Coplanar stripline components for high-frequency applications,” *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 1725–1729, Oct. 1997.



Khelifa Hettak was born in Tizi Ouzou, Algeria, in 1966. He received the Dipl.-Ing. degree in telecommunications (with distinction) from the University of Algiers, Algiers, Algeria, in 1990, the D.E.A. degree in signal processing and telecommunications from University of Rennes 1, Rennes, France, in 1992, and the Ph.D. degree in signal processing and telecommunications (with the highest distinction) from the Ecole Nationale Supérieure des Télécommunications (ENST), Brest, France, in 1996.

He was with the Electronics and Telecommunications Systems Laboratory, France Telecom, ENST. In January 1997, he joined INRS-Télécommunications, a research center of the University of Québec, **<City,>** QC, Canada, as a Researcher, where he was involved with the Wireless Systems for Direct Access to Subscribers and Millimeter Wave LAN Project and on an optical fiber backbone for Broadband Indoor Wireless Personal Communication Systems supported by Bell-Quebec/Nortel/Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canadian Institute for Telecommunication Research (CITR), respectively. In October 1998, he joined the Electrical Engineering Department, Laval University, as an Associate Researcher, where he was involved in RF aspects of smart antennas. Since August 1999, he has been with the Terrestrial Wireless Systems Branch, Communications Research Centre (CRC), Ottawa, ON, Canada, where he is currently a Research Scientist involved with developing MMICs at 60 GHz, low-temperature cofired ceramic (LTCC) packaging, and RF microelectromechanical system (MEMS) switches. His research activities include the development of new millimeter-wave technologies for telecommunications and detection systems, integrated smart antennas for wireless systems, the design of various microwave/millimeter-wave integrated circuits, numerical methods. and indoor radio propagation channel characterization.

Dr. Hettak was the recipient of the France Telecom Scholarship.

Tony Laneve received the Bachelor of Engineering and Master of Engineering degrees from Carleton University, Ottawa, ON, Canada in 1991 and 1995, respectively.

From 1994 to 2000, he was with the Communications Research Centre, Ottawa, ON, Canada, where he was involved with research in GaAs MMICs and RF MEMS. In 2000, he joined the GaAs heterojunction bipolar transistor (HBT) MMIC Design Group, Nortel Networks Optical Components Corporation, Ottawa, ON, Canada, where he is currently involved with MMIC design for millimeter-wave applications.

Malcolm G. Stubbs received the B.Eng., M.Eng., and Ph.D degrees from the University of Sheffield, Sheffield, U.K., in 1970, 1972, and 1976, respectively.

From 1975 to 1978, he was with the Communications Research Centre (CRC), Ottawa, ON, Canada. Upon his return to the U.K., he joined the Allen Clarke Research Centre, Caswell, U.K., where he was engaged in GaAs MMIC research. In 1981, he rejoined the CRC as a Staff Member, where he is currently responsible for the development of planar microwave and millimeter-wave circuits. His interests include the modeling and application of MMICs, MEMS, and LTCC technologies to high-frequency communications systems.

Dr. Stubbs was the recipient of a National Research Council Post-Doctoral Fellowship.