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6. AUTHORS  Zoya Popovic	

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13. ABSTRACT (Maximum 200 words)  
During the duration of this award we have demonstrated the following: (1) the first quasi-optical bidirectional amplifier array; (2) the array was used in a communication system and shown to have improved performance related to multipath fading due to built-in angle diversity; (3) the first quasi-optical isolator with no ferrite components, operating at X-band; (4) a two-stage quasi-optical lens amplifier array with improved feed efficiency and a cost of \$85 /watt; (5) the first optically-controlled half-duplex T/R quasi-optical amplifier array with the possibility of extremely high-speed switching between transmit and receive functions. We also demonstrated a multi-user frequency reuse communication system based on the built-in angle-of arrival properties of lens amplifiers. 5 continued funded projects resulted from the accomplishments achieved under this award.

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FINAL REPORT, APRIL 30, 2000

1. **ARO proposal number:** 34962-EL
2. **Period covered by report:** August 1, 1996 – January 31, 2000.
3. **Title of proposal:** Quasi-optical transceivers for wireless data communications
4. **Grant number:** DAAH04-96-1-0343
5. **Name of institution:** University of Colorado, Boulder.
6. **Author of report:** Zoya Popović
7. **List of manuscripts published/submitted under ARO sponsorship:**

[1] "A quasi-optical isolator," S. Hollung, W. Shiroma, M. Marković, Z. Popović, *IEEE Microwave and Guided Wave Letters*, Vol. 6, No. 5, 1996.

[2] "A bi-directional quasi-optical lens amplifier," S. Hollung, A. Cox, Z. Popović, *IEEE Trans. on Microwave Theory and Techniques*, Vol.45, No.12, pp. 2352–2357, December 1997.

[3] "A bi-directional quasi-optical lens amplifier," S. Hollung, J. Vian, Z. Popović, *IEEE MTT-S International Microwave Symposium Digest*, pp. 675–678, June 1997, Denver.

[4] "Quasi-optical transmit/receive front ends," Z. Popović, A. Mortazawi, *invited paper*, *IEEE Trans. on Microwave Theory and Techniques*, Vol. 48, No. 11, pp. 1964–1975, November 1998.

[5] "A two-stage amplifier lens array," T. Berg, S. Hollung, J. Lee, Z. Popović, *The 28th European Microwave Conference Digest*, pp. 178–183, October 1998, Amsterdam, The Netherlands.

[6] "A 10-GHz high-efficiency lens amplifier array," E. W. Bryerton, M. D. Weiss, Z. Popović, *IEEE MTT-S International Microwave Symposium Digest*, pp. 1461–1464, June 1998, Baltimore.

[7] "An optically-controlled transmit/receive active antenna," J. Vian, P. Kirkpatrick, Z. Popović, *9-th Annual DARPA Symposium on Photonic Systems for Antenna Applications Proceedings, Session 10, PSAA-9*, Monterey, CA, February 1999.

[8] "Switched-mode high-efficiency microwave power amplifiers in a free-space power combining array," T. Mader, E. Bryerton, M. Marković, M. Forman, Z.B. Popović, *IEEE Trans. on Microwave Theory and Techniques*, Vol.48, No.10, pp. 1391–1398, October 1998.

[9] "Quasi-optical components and subsystems for communications," Zoya Popović, *Invited talk, 1995 ISSSE Symposium Digest*, San Francisco, November 1995.

[10] Chapter for a Wiley book, Eds. K.C. Gupta and P. Hall (to be published in February 1998): "Analysis and design of oscillator grids and arrays," W. Shiroma, E. Bryerton and Zoya Popović. (40 pages)

[11] "Quasi-optical antenna array amplifiers," Zoya Popović, Robert York, Emilio Sovero, Jon Schoenberg, Chapter 5 in *Active and Quasi-optical Arrays for Solid-State Power Combining*, eds. R.A. York and Z. B. Popović, John Wiley & Sons, 1997, pp. 187-244.

[12] "Grid oscillators," Zoya Popović, Wayne A. Shiroma, Robert M. Weikle, II, Chapter 8 in *Active and Quasi-optical Arrays for Solid-State Power Combining*, eds. R.A. York and Z.B. Popović, John Wiley & Sons, 1997, pp. 293-330.

[13] "Quasi-optical subsystems," Zoya Popović and Gerald Johnson, Chapter 12 in *Active and Quasi-optical Arrays for Solid-State Power Combining*, eds. R.A. York and Z.B. Popović, John Wiley & Sons, 1997, pp. 455-484.

[14] *Popular Press*: "T/R lens amplifier antenna arrays for X-band and Ka-band," Z. Popović, *Invited Cover Feature, Applied Microwave and Wireless*, pp.30-45, February 1999.

#### 7. Ph.D. theses:

- *Quasi-Optical Transmit/Receive Lens Amplifier Arrays*, Ph.D. Thesis, Stein Hollung, University of Colorado, Boulder, 1998.
- *High-efficiency Switched-mode Microwave Circuits*, Eric Bryerton, Ph.D. Thesis, University of Colorado, Boulder, 1999 (partially funded by this award).

**8. Personnel supported:** Stein Hollung (Ph.D. graduate student), Eric Bryerton (partial support, graduate student), Zoya Popović (5% time AY).

**9. Other:** I was one of the organizers of the Workshop on Quasi-Optical Power Combining, held in Santa Barbara in March 1997. The two-day workshop was sponsored by ARO and DARPA and was attended by invitation only by key university, industry and government researchers in this field. A report submitted to ARO summarized the conclusions of the workshop. In my opinion, the workshop was worthwhile and successful.

One of the conclusions of the workshop was that functionality of quasi-optical combiners is possibly their most promising advantage over conventional architectures. This grant

funded the first demonstrations of functional quasi-optical combiners: T/R modules and quasi-optical isolators.

I also co-edited a book, with Prof. Bob York from UCSB and published by Wiley entitled *Quasi-optical and active arrays for spatial power combining*. This book summarizes the work done mainly under ARO funding in the past decade. Dr. Jim Harvey from ARO, together with Caltech Prof. David Rutledge wrote the preface to the book. The book sold out at the IEEE International Microwave Symposium the year it came out.

During the duration of this grant, the PI received the following recognitions:

- International URSI General Assembly Issac Koga Gold Medal, for work in active antenna arrays, Lille, France, 1996.
- Margaret Willard Award, as professional womens's role model, University of Colorado, 1997.
- Eta Kappa Nu professor of the year, awarded by students, 1997.
- Elected a Senior Member of the IEEE, 1999.
- Promoted to Full Professor, January 2000.
- Awarded the Humboldt Research Award from the German Alexander von Humboldt Foundation, 2000.
- Published textbook *Introductory Electromagnetics*, Zoya Popović and Branko Popović, Addison Wesley/Prentice Hall, 1999.

*New directions resulting from this work:*

The PI is/was a participant of the following funded projects that were a direct result of this award:

- MAFET Thrust 3, partner with Lockheed Martin, demonstrated first 5-W Ka-band quasi-optical combiner (designed at CU) and subsequent 25-W Ka-band combiner was demonstrated by Lockheed.
- ARO MURI in Quasi-Optical Power Combining, Clemson University, participated for 1 year in the project.
- ARO MURI in Quasi-Optical Power Combining, subcontractor to Caltech. Tasks: Half and full duplex T/R quasi-optical arrays; high-efficiency X-band arrays.
- ONR MURI in RF photonics. Tasks: optical control of quasi-optical T/R arrays, optical processing of microwave signals from antenna arrays.
- NSF grants (2) in wireless communications. Tasks: adaptive quasi-optical arrays; quasi-optical receivers with angle and polarization diversity.

## BRIEF OUTLINE OF RESEARCH FINDINGS

There are several projects that have been in part funded by this grant. They are all related to functionality of quasi-optical power combiners. A brief description of research findings for each of the projects is outlined below. Publications are attached.

### A. A quasi-optical isolator

A non-ferrite X-band quasi-optical isolator was demonstrated for the first time. The isolator consists of a linear-to-circular polarizer and an absorbing tuner grid. It can be used in front of a quasi-optical amplifier to prevent high-level reflections and instabilities. It produces at the same time a CP wave from a LP amplifier. The isolator was demonstrated at X-band with...

*This work was reviewed in the Microwave Journal*

### B. Quasi-optical T/R module

During the first year of the grant, the first quasi-optical T/R module was demonstrated at X-band. The T/R module consists of a lens amplifier array and a grid oscillator first-level combining feed/receiver. In transmission, the grid oscillator radiates a power-combined wave from a focal point of the lens amplifier array. In the lens, vertically-polarized antennas in each unit cell receive the wave, route it through SPDT switches to MESFET power amplifiers and then to horizontally-polarized output antennas. The collimated output beam combines the powers of all the amplifiers in free space. In reception, a horizontally-polarized input wave is received by each antenna element, routed to a LNA and then to the vertically-polarized antenna. This received wave is then focused on to the grid oscillator, which now acts as a self-oscillating mixer.

Results of the entire array are presented in detail in papers [2,3,4]. In the second year of the grant, we have characterized some functionality properties of the lens. One very interesting advantage of such an array if used in communication systems is its behaviour with respect to multipath fading in a mobile or indoor environment. The fading properties were measured in the following way. A mirror was translated and rotated along the direct path between a horn transmitter and the lens amplifier in receive mode. The multipath peak to null ratio was measured as a function of reflector position and then compared to this ratio with no lens amplifier. It was shown that there is about a 50 dB improvement in the susceptibility to multipath fading when the lens amplifier is used. We have found this to be true due to several reasons: (1) the array pattern alone helps reduce multipath effects; (2) the amplifiers add gain, and since their noises are not correlated, the dynamic range is increased; (3) if several receivers are used along a focal arc, the lens has built-in angle diversity (as was demonstrated in an earlier paper, and verified here).

Another experiment was done to demonstrate a frequency reuse multiuser FSK-modulated communication link. Here the two channels are separated spatially along the focal surface, so that the same carrier can be used. The isolation between channels was greater than 15 dB, in accordance with specs in wireless systems.

### C. Two-stage lens amplifier combiner

Another new combiner was demonstrated at X-band and is described in detail in publication [5]. In this array, two-stage amplifiers are used in each unit cell with patch antennas in a multilayer design. The amplifier array is built with low-cost devices, and the power cost amounts to 85\$/Watt with an output ERP of 50 W and a power of about 1 W. The combining efficiency was greater than 75%. The 14-element array exhibited an active gain of 9.5 dB when compared to an identical passive lens with through lines instead of amplifiers.

Some interesting properties of lens amplifiers were measured on this amplifier. The on/off ratio (gain) was first measured with one antenna transmitting from the far field, and another receiving the amplified signal at a focal point a distance  $F$  away from the center of the array (where  $F$  is the focal distance). Then the feed horn was moved to a distance  $2F$ , and the receive horn also to a distance  $2F$ . Very similar gains of 9.3 and 8.9 dB were measured in the two cases, and the power levels confirmed the lensing properties of this array. In the next experiment, an improved packaging scheme was tested. A metal enclosure (similar to an over-moded horn antenna) was made at the feed end. The measurement shows practically identical behaviour of the lens with and without the metal enclosure, indicating again good focusing and reasonable feed efficiency. Phase shifterless beam steering up to 30 degrees with side lobe levels below 12 dB was also demonstrated by moving the feed horn along the focal arc.

### D. Quasi-optical high-efficiency lens arrays for transmission

In quasi-optical amplifier arrays, the heat is produced across the entire area of the array, while the heat sink can only be placed at the perimeter, since the arrays operate in transmission. Elevated temperatures have been shown to reduce the value of the gain as well as the uniformity of the gain across the array. In order to reduce the heat as well as power consumption of the arrays, we have studied high-efficiency power amplifier arrays operating in switched-mode (classes E and F). This work resulted in a class-F X-band lens array using commercial Fujitsu FLK052 packaged MESFETs. The array was designed as a lens to increase the overall efficiency. The lens has the following properties: focal length of 11 cm ( $F/D=0.5$ ) for minimized feed loss, inter-element spacing of  $0.91\lambda$ , 28 elements in a triangular lattice, so far up to 8 elements populated with class-F amplifiers. A single amplifier was measured to have an output power of 28.6 dBm, with a saturated gain of 8.6 dB at 8 GHz, and a drain efficiency of  $\eta_D = 73\%$  and power-added efficiency of  $PAE = 61\%$ . The effective radiated power was measured for 2, 4 and 8 elements of the lens populated, and increased from 38 dBm to 42 dBm to 48 dBm as the number of elements was increased. With 8 elements, the ERP of 59 watts was measured with an antenna gain of 11.4 dB, and an output power of about 5 watts with 69% drain efficiency was calculated. These are the highest efficiencies reported to date on QO arrays, and we believe also in any amplifier using a commercial packaged device. The power cost in this array was estimated to be \$65/watt. The background theory and preliminary measurements of a high-efficiency array are presented in publication [8] listed above. The work described here, which was started under this award, is still in progress, funded by a ARO MURI on quasi-optical

power combining, where the PI is a subcontractor to Caltech.

#### **E. Optical control of QO transmit/receive arrays:**

In the T/R arrays demonstrated to date, the transmit and receive functions are controlled through microwave SPDT switches that route the signal through the LNA or PA paths. The switches in the KA band array described above in item 1, are fast (2nsec), but are all biased in parallel, and therefore the response is slow. The reason is that the capacitances and resistances add up, increasing the RC time constant. An architecture in which each element of a large array would be addressed separately is very complicated and would greatly reduce the stability of the array due to coupling between the control and T/R circuitry. In order to investigate an architecture in which each element can be controlled separately without performance degradation and with increased switching speed, we have developed an element of a lens in which the signals are routed via an optically-controlled microwave switch. This work has started recently, and we have shown that the array element can be switched with very low optical power ( $1 \mu\text{W}$ ) by controlling the bias of a FET, which biases 2 pin diodes. This optical-microwave switch currently exhibits several GHz bandwidth with 30 dB isolation. Details of the first demonstrated version are given in publication [7] listed above. In the next stage of the work, we are implementing an entire array. This work will continue to be supported under an ONR MURI project, in which the University of Colorado is the lead team member.