Chapter 10
Overall Conclusions and Possible Future Directions

Active integrated antennas have found numerous applications as phased arrays, retro-directive arrays, and spatial power combiners. Coupled-oscillator antenna arrays represent a very exciting subset of active integrated antennas both from an application point of view, as well as from a research and analysis point of view, due to some very attractive properties, such as their ability to produce arbitrary phase shift distributions, as well as their capabilities of frequency conversion and frequency generation. In addition, they inherit the practical advantages of active integrated antennas, which are compact low-profile circuit implementations that are compatible with low-cost fabrication technologies (such as microstrip and coplanar waveguide), using single and multilayer printed circuit boards.

As we have seen, however, the design of coupled-oscillator antenna arrays, is far from trivial due to their highly nonlinear nature, which results in a dynamical behavior that is difficult to simulate and predict accurately and, in effect, increases the difficulty of designing coupled-oscillator arrays demonstrating a robust performance. Nonetheless, the progress of nonlinear circuit simulation and optimization techniques and the increase in computational power of low cost personal computers has made possible the accurate analysis of coupled-oscillator arrays with as many as a few tens of elements via combining sophisticated nonlinear models for the active devices and electromagnetic analysis for the antenna, transmission lines, and interconnects, using the various methods described in Chapter 8. Efficient analysis of large coupled-oscillator arrays requires the use of approximate perturbation models, infinite-array approximations, and the continuum model that enable understanding of the exhibited behavior at a level permitting design of functional systems. The intuitive understanding of the array behavior and the gain in computational efficiency resulting from application of such methods makes them indispensable tools, complementary to the fully nonlinear simulators. The description and use of such methods has been the focus of Chapter 1 through Chapter 7.

Interest in low-cost, high-performance radio-frequency systems with reconfigurable properties in terms of transmitted beam direction or polarization makes coupled oscillator arrays a strong candidate for many applications including radar, phased arrays, and imaging in the microwave and millimeter wave frequencies. There are still numerous challenges to be addressed and many areas where improvements in coupled-oscillator array technology are desirable. Among these we specifically note the application of new implementation technologies in the design of coupled oscillator arrays, such as substrate integrated waveguide (SIW) technology and the creation of conformal coupled-oscillator arrays using flexible substrate materials such as paper and liquid crystal polymers (LCP). Preliminary results concerning coupled-oscillator arrays using SIW technology were discussed in Chapter 6, demonstrating the possibility of low-cost single substrate array implementation. On the other hand, fully integrated coupled-oscillator arrays in the millimeter-wave frequencies have also appeared in the literature [161] paving the way for the introduction of coupled-oscillator arrays in millimeter-wave phased-array sensing and communication applications.

We further note, that successful demonstrations of only small arrays have been reported in the literature to date, and large arrays employing hundreds of elements remain to be seen. In such large arrays, perimeter oscillator control of the radiated beam will be particularly beneficial. Furthermore, the demonstration of coupled-oscillator arrays using signal processing and optimization techniques in beamforming, and more importantly adaptive beamforming, is an area that should be further exploited. Finally, a number of challenging analysis problems remain to be addressed, such as quantifying the effect of phase noise on the locking range of the array and more detailed study of mode locking for pulsed operation of coupled oscillators in the microwave frequencies.

Despite the progress in the theory and design of coupled-oscillator arrays during the past two decades, active antenna arrays based on coupled oscillators have not yet found widespread practical application, although there have been notable achievements in array implementations such as the ones shown in

Chapter 6. It is hoped that the material presented in this book demonstrates the potential of coupled-oscillator arrays and motivates deigners to apply them in microwave and millimeter-wave array antennas.

We have endeavored to provide the reader with the understanding and the tools for such application through description of the research to date and mention of a few areas for further study and technological development. The references to the archival literature will, of course, provide more detail than could be included here without rendering the presentation far too cumbersome for the casual reader. However, the literature sometimes presupposes significant familiarity with the approaches currently in vogue. Thus, in parts the present treatment is an overview of the research work while in other parts it provides a tutorial facilitating access to the literature. We hope to have struck a balance between these two styles of presentation resulting in a book of somewhat wider utility in this field than would be the case for either style alone.