Abstract—Optics and radio-frequency electromagnetics now both need to work with many distinct channels for communications and sensing. A common framework, based on singular-value decomposition, clarifies the number of degrees of freedom and the true nature of orthogonal communications modes, and resolves many paradoxes. This approach leads to fundamental results in optics and electromagnetics, and maps well to recent advances in complex optical interferometric circuits for handling multi-mode fields.

Keywords—degrees of freedom, modes, channels, optics

Traditional optics and radio-frequency waves historically represented two extremes of electromagnetics. An optical lens works in parallel with millions of pixels, directions, or spatial channels, whereas a Hertz dipole broadcasts essentially just one spatial channel that encompasses nearly all directions. Furthermore, because of the \( \sim 10^{15} \) Hz frequencies of optics, nearly all optical detection is essentially by counting photons; photon energies are in the range of electron-volts, which is much larger than the \( \sim 25 \text{ meV} \) of thermal energies at room temperature. The optical field has too high a frequency for us to measure the field amplitude in time, and simple photon detection generally loses all phase information in the field. By contrast, in radio-frequency electromagnetics, classical descriptions of fields and their measurement are more than adequate in nearly all circumstances, and the full amplitude and phase of the electromagnetic field is directly measurable.

The need for more channels for communication and greater specificity in sensing is, however, pushing up the optics and radio-frequency electromagnetics closer. Wireless radio-frequency communications needs more spatial channels, and optics has a growing need to have deeper control and analysis of moderate numbers of channels, including the phase behavior. In optical communications, for example, we may want to use multiple channels in one multi-mode fiber or in free-space communication links, and in optical sensing, we may want to make more use of the information in the phase of the field, not just the intensity or power. A classic problem for optics has been how to separate multiple overlapping light beams, without being able to directly measure the field at multiple different points, or without incurring massive power loss by splitting the beam into multiple replicas to resolve beams of different shapes with spatial filters.

A problem for both optics and radio-frequency electromagnetics has been how to correctly describe these different channels. A common approach has been to try to reuse ideas of “modes” that were originally devised for resonators or for propagating modes in waveguides. However, such “modes” do not correctly describe the communications channels, especially in free-space systems, and their use has led to a great deal of confusion, both in optics and radio-frequency electromagnetics; there has been particular confusion around whether so-called “orbital angular momentum beams” give us new or even infinite numbers of channels (to which the answer is “no” in both cases [1]).

Recent work from optics has clarified the issue of the correct channels or degrees of freedom for communication [1, 2], and given us the fundamentally correct way of describing scattering objects or optical devices [1]. This work, based on singular-value decomposition, establishes so-called “communications modes” and “mode-converter basis sets” that resolve these issues, for both optics and radio-frequency electromagnetics; in particular, this work gives unambiguous answers to the number of usable spatial communications channels. At the same time, the field of optics has recently been able to start exploiting the fabrication complexity of silicon photonics circuits. New architectures and algorithms [3-7], with a clear link to the SVD mathematics [1], are allowing a remarkable new level of control in complex optical systems, including, among other things, the resolution of the problem of how to separate multiple overlapping light beams without loss [1,2]. Some of these optical systems can configure themselves, including even automatically finding the best communication channels through complex scattering systems [6,7]. This paper will introduce and summarize these developments and the prospects in these fields for optics and in electromagnetics more generally.

REFERENCES