

CONCLUSIONS

In this chapter we discuss applications and future work regarding the different aspects of the research presented in this thesis. This thesis revolves around one fundamental photorefractive interaction, the two-beam coupling effect. The contributions described in this thesis are divided into three aspects of photorefractive systems: The first is that of developing a component technology, which includes the demonstration of the two-beam coupling modules described in chapter 2 and by the study of the oscillating patterns occurring inside a barium-titanate spherical disk, in particular the triangle pattern, described in chapter 3. The second is that of building and optimizing a specific photorefractive application, the carrier suppressor, described in chapter 4. Finally, the third is that of developing an analytical tool that can simplify the modeling and prediction of photorefractive systems. In this case, the contribution is the presentation of a general solution for the operator theory in the case of a single spatial mode in each beam, described in chapter 5. These different aspects sometimes overlap. For example, the operator theory provided a model on which to cast the carrier suppression effect, resulting in an understanding of the system which proved to be crucial for its optimization. Below, we give concluding remarks and related applications on the topics covered in this thesis.

The fiber-interconnected two-beam coupling modules are pre-aligned building blocks for photorefractive system design. They provide a way to quickly test an idea without having to invest the time in critical optical alignment which is necessary

when building a conventional system. However, it is important to note that, because the geometry within a module is fixed, they are not well suited for optimization of systems. The utility of the two-beam coupling modules as a component technology was illustrated in the example given in section 2.5, where the inclusion of a reflexive-coupling unit in the autotuning filter's ring provided an increase of the output contrast between two signals which are being separated. It took only a few minutes to include the reflexive-coupling element and test the performance. Future work on the modules should seek to improve their long term stability. In section 2.4 some suggestions for future designs were given, but the main issue to keep in mind in a new design is that the adjustments be external to the final module, thereby reducing the susceptibility to long term alignment drifts. Among the useful applications of the modules, we suggest that of testing different ring configurations. Because the geometry of the modules are fixed, the differences in behavior can then be attributed to the different architectures and not to the geometrical factors of the two-beam coupling configurations. For example, one can compare the behavior of the autotuning filter architecture shown in figure 2.10 (b) with one where the pump crystal is instead located in the reflexive loop (directly in front of the plus input port of the reflexive coupling crystal). Understanding the different rings could result in new ideas for future oscillator-based photorefractive processors.

We believe that our research group is the first to observe the oscillating patterns occurring within a barium-titanate spherical disk. For now, the oscillating patterns observed inside the spherical disks stand mostly as a scientific curiosity, however, in order to devise possible applications for this phenomenon, it is necessary

to first understand it. In fact, the model presented in section 3.4 suggests that the disk patterns are unidirectional miniature oscillators pumped mostly by a single two-beam coupling interaction, and therefore hold the promise for a future integrated ring processor such as the autotuning filter [Anderson, '92].

As part of a system oriented group, it is natural that within the contributions is that of building and optimizing a photorefractive system for a specific processing task, in this case, that of carrier suppression. The carrier suppressor was developed for a specific application as part of a higher level system, where its function is to remove the correlation between temporal signals which are to be discriminated by the next stage, the autotuning filter. Another application for the carrier suppressor demonstrated in chapter 4 would be in laser tuning. In Ye *et al* [Ye, '96] a laser beam, whose frequency is to be tuned, is shifted by an acousto-optic modulator and then locked to a reference cavity. In this case, the reference cavity is locked to the ^{87}Rb D_2 line at 780 nm, however the same concept could be used with the I_2 hyperfine resonances at 532 nm [Jungner, '95]. The carrier suppressor used on such a system would allow the use of electrooptic modulators, therefore providing higher modulation bandwidth and, thus, shorter reference cavities which are typically easier to stabilize. The carrier suppressor described in chapter 4 was the evolved result of several other carrier suppressor predecessors. The earlier systems were not covered by this thesis because, first, they didn't accomplish the specifications of our application, and second, all the important aspects of the carrier suppression physics is covered in the description of the last, optimized system. This system rendered a suppression of more than 70 dB, the highest value reported in the literature [Loayssa,

'00; Tonda-Goldstein, '00]. Despite this successful result, there is room for improvement in other aspects of the system. Section 4.4 provides preliminary results in the implementation of a future carrier suppressor which utilizes a channelized electrooptic modulator design. Although the integration provided by this design is attractive for two or three channels, as the number of channels increases, we believe this design will prove impractical due to crystal size and cross-talk issues. In that case, a possible alternative design is that of using a grating to direct the several beams to independent modulators which are, however, placed next to each other on the same mount.

Finally, in chapter 5, we present a closed-form solution for two-beam coupling for the case of only one spatial component on each port. This solution is cast in terms of an operator algebra which was originally developed by Anderson [Anderson, '00; Anderson, '99] and is summarized in section 5.2. We believe that the solution presented is the most general available in the literature as it includes both complex coupling and any number of temporal components. The work of Saxena *et al* [Saxena, '90] solves the problem of N mutually incoherent pairs of temporal beams. In this case, they show that complete energy transfer between the two write beams may occur in a finite interaction length, as opposed to the infinite thickness required in the standard case of only one temporal component on each beam. This is the same conclusion we arrived at, for example, in the case of the carrier suppression, where the presence of a sideband allowed for perfect suppression at a finite interaction length. However, their solution includes only the case for real coupling, this is, pure energy transfer. The work from Ringhofer *et al* [Ringhofer, '00] provides the general

complex coupling solution for a phase modulated beam in the gain port, with arbitrary phase modulation strength. However, their solution describes only two temporal components, the carrier and the modulation sidebands, as opposed to an unlimited number of temporal modes as in the solution provided in chapter 5.3. In their paper they also provide an application example, where phase modulation is used in the active stabilization of two-beam coupling by means of an electronically introduced phase feedback. For the case of a single spatial mode on each beam, besides the signal processing applications in our laboratories, such as the demultiplexer [Saffman, '91] or the autotuning filter (previously known as the feature extractor) [Anderson, '92], other applications include RF filtering [Hong, '93], laser bandwidth narrowing [Chomsky, '91] or signal amplification [Hamel de Monchenault, '87]. An application that has currently been brought into the spotlight is that of using heterodyne detection with two-beam coupling for laser ultrasonics [Ing, '91; Puoet, '96; Scruby, '90]. Heterodyne detection with two-beam coupling offers several advantages over the conventional optical heterodyne scheme [Hamel de Monchenault, '88]: First, the signal beam may consist of an arbitrary wave-front, such as speckles for instance, while, in the conventional heterodyne, the signal is limited to a spatial mode which is collinear with the local oscillator plane wave. Second, since the grating adapts to the incident signal wave front, the heterodyne detection is not susceptible to time varying phase distortions which are slow compared to the photorefractive response time. The photorefractive heterodyne detection is well suited for laser ultrasonics, a noncontact method for performing ultrasonic nondestructive evaluation measurements. Unlike the conventional piezoelectric

contact transducers, the noncontact nature of laser ultrasonics allows inspection in high-temperature or otherwise hostile environments. The method typically consists of generation of ultrasound with a high-power pulsed laser followed by detection of the ultrasonic motion of the scattering surface by a photorefractive heterodyne detection setup (see, for example, [Murray, '00]).

In conclusion, this thesis covers important aspects in the development of photorefractive system that utilizes two-beam coupling. It covers, first, the development of component technologies which allow for easy testing of concepts, second, the development of a specific processing system, the carrier suppressor, and finally, it provides a solution for the general case of a single spatial mode two-beam coupling cast in terms of an operator formalism.