

# CHAPTER 1

## INTRODUCTION

### 1.1 Overview

This thesis aims to demonstrate the potential usefulness of photorefractive circuits in microwave signal processing. Photorefractive crystals are nonlinear holographic materials with a short-time memory and the ability to couple coherent optical beams at low intensities. We take advantage, as most modern optics based communications, of the fact that a narrow band device at optical frequencies translates into a broadband device at microwave frequencies [1]. The photorefractive volume gratings, with which we deal in this thesis, typically have lengths on the order of half a centimeter. This gives them a Bragg matched bandwidth of hundreds of gigahertz, amply sufficient to cover microwave frequencies.

Prof. D.Z. Anderson's group has a long history of information processing with photorefractive circuits. Our group has specialized in manipulating signals with novelty filter two-beam coupling configurations [2-5] and self-organized photorefractive resonators [6-9]. Circuits were built that performed processing tasks such as demultiplexing signals carried by different frequencies [10], or present on the input at different times [11], as well as controlling the relative intensities of signals [12]. The photorefractive community commonly employs resonators to design information processing circuits [13-22], and less often, novelty filters [23]. This thesis concentrates on possible uses of an oscillator-based photorefractive

circuit for microwave signal processing. The circuit extracts the largest principal component [24] of its input signal space. We mainly refer to it as the “autotuning filter” for reasons that will be explained later. The filter’s design is a variation on the feature extractor’s design previously reported on by Mark Saffman [25]. This thesis also shows the application of the novelty filter configuration to the suppression of the optical carrier of phase-modulated beams at microwave frequencies. The work on carrier suppression was pioneered by Valeria Damiao [26] and so this report presents only the basic principles that are necessary for contextualizing our use of it.

### 1. 1. 1 The photorefractive effect

Depending on the photorefractive material, two-wave mixing may transfer phase information between coherent beams or energy or a combination of both. The coupling constant  $\Gamma$  characterizes the exchange.  $\Gamma$  is purely imaginary for materials in which drift dominates the movement of free carriers generated by photoexcitation. Such materials record holograms that couple only the phase information of coherent beams.  $\Gamma$  is purely real for diffusion dominated materials that couple only the energy of interfering beams [27]. Energy transfer results from a  $\pi/2$ -phase shift between the light interference pattern and the index modulation it generates. A more in depth explanation of the phenomenon may be found in textbooks such as [28, 29].

The optical circuits presented in this thesis use barium titanate ( $\text{BaTiO}_3$ ) crystals as photorefractive media, which is a diffusion-dominated material [30]. The coupling constants of these crystals commonly reach  $20 \text{ cm}^{-1}$ . The value of  $\Gamma$  indicates the potential depth of the index modulation and thus represents the potential diffraction efficiency of the photorefractive grating. The effective  $\Gamma$  in experiments, depends on the geometry of the beams and the orientation of these beams relative to the c-axis (or optical axis) of the birefringent crystal.

Two-beam coupling in barium titanate is analogous to an electronic transistor. A transistor has two inputs and one output. The output current is an amplified copy of one of the currents coming in. The extra current is provided by the non-amplified input. Two-beam coupling requires coherent input beams. In the crystal, one beam undergoes amplification, keeping all its spatio-temporal characteristics, at the expense of the other input beam's energy. The latter beam is often referred to as the "pump" beam. This optical transistor outputs both the amplified and the de-amplified beams. Its small signal gain is given by

$Exp[\Gamma L]$  where  $L$  is the length of the grating in the material. For a typical 5 mm grating and a pump-to-small-signal ratio of  $10^5$ , gains reach 20 000 or 40 dB.

Of particular interest in this work, is two-beam coupling with temporally modulated beams. The coupling beams may be modulated with more than one signal. If the various signals are temporally uncorrelated, they photorefractively couple as if they were the only signal present but with a modified coupling constant. Each signal experiences a coupling constant diminished by the ratio of their own intensity to the total intensity in the crystal. For example, the small signal gain for each temporal component is  $Exp[I_{\text{signal}}/I_{\text{total}} \cdot \Gamma L]$ . The fact that the available gain is finite means that when more signals are present the less each signal gets amplified. This phenomenon is one of the basic building blocks for the designs of our competition-for-gain driven photorefractive circuits.

The photorefractive material's memory provides another building block for the design of our circuits. The time constant of barium titanate is on the order of milliseconds to seconds depending on the total intensity of the light. A photorefractive index modulation therefore, mimics the light patterns the material is submitted to, but integrated over time. In other words, these holograms do not record the simple multiplication of the electrical fields generating the interference patterns, but rather the correlation of those fields over a few seconds. This correlation function is essential for the autotuning filter's ability to distinguish signals among a collection of uncorrelated signals. Milliseconds are an unnecessarily long time to integrate radio frequency signals for correlation. The slow time constant of barium titanate limits the adaptation speed of the autotuning filter to abruptly changing input signals. It also limits the lowest frequency of the signals it can process to a few kilohertz. The time constant does not, however, affect the processing of higher frequency signals.

### **1. 1. 2 The autotuning filter**

The autotuning filter is designed to separate out the strongest uncorrelated signal from its spatio-temporal input space. This space refers to multiple coherent optical beams carrying amplitude and/or phase information. The strongest uncorrelated signal is closely related to the largest principal component of the input space. This relationship is clarified in the theoretical section 2. 4. 2. 1. Throughout this thesis, however, the terms “stronger signal” and “largest principal component” are used interchangeably.

The autotuning filter is fundamentally an optical ring oscillator in which gain is supplied by photorefractive two-beam coupling [31-39]. The input beams “pump” the gain medium. The cavity modes of the oscillator intersect these pump beams inside the photorefractive crystal aligned to transfer the most energy to the oscillating beam. The oscillation starts with scattered light from the pump beam that is naturally emitted in the direction of greatest gain. This fanning phenomenon [40] is a result of local photorefractive two-beam coupling between the scattered light and the propagating beam.

Figure 1.1 illustrates the design of the autotuning filter. The crystal on the left-hand side of the ring is the gain medium mentioned above that couples the input beams to the oscillating beam in the ring. The additional photorefractive crystal on the right-hand side of the ring, acts as a selective loss element. It “absorbs” a signal inversely proportionally to its power. Since the gain medium amplifies proportionally to a signal’s relative strength, the two photorefractive interactions combine to facilitate the oscillation of only the largest principal component in the ring. In steady state, the other principal components remain on the pump beams at the output of the gain crystal. The filter effectively extracts the strongest signal from its input. That signal may be retrieved by sampling the oscillating beam of the

resonator. Thus the filter potentially has two outputs: one output to provide the strongest signal and the other output to provide all the other signals.

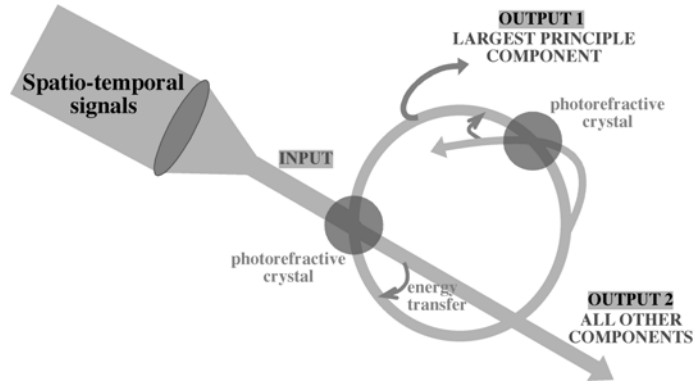


Figure 1.1. Schematic diagram of the autotuning filter.

Which (if not both) output is of interest depends on the application. For example, if the input beams are carrying a mixture of a weak signal and a strong jammer, output #2 (referring to Figure 1.1) delivers the desired signal while the ring extracts the unwanted jammer. If the input mixture contains a signal with much additive noise, then output #1 provides a noise-reduced signal. If all the principal components of a collection of information carrying beams need to be extracted then “daisy-chaining” autotuning filters at the #2 outputs yields the extracted components at the #1 outputs.

Many more applications can be found in the vast field of principal component analysis (PCA) [24]. PCA is a fundamental tool in the analysis of statistical data. It is generally a computer intensive method relegated to the post-recording processing of data. Real-time, adaptive principal component extraction is in its infancy. As digital signal processing techniques improve [41, 42] and the complexity of neural networks increases [43, 44], PCA finds applications in low frequency wireless communications. Neural network architectures have added adaptive capabilities to principal component extractor circuits [45, 46]. Those

implementations are computer based however and are therefore also signal bandwidth limited.

The optical filter discussed in this thesis is 5 cm<sup>2</sup> in size and extracts the principal components of up to 3-GHz bandwidth signals in seconds. Although the filter is based on an optical resonator, the photorefractive dynamics give the device adapting capabilities. For example, the circuit keeps track of slow drifts of the optical and the signal carrier frequencies. We believe that the literature presents no other optical adaptive extractor of spatio-temporal principal components. Most optical systems involving PCA realize pre-determined pattern recognition [47-50], or analyze and classify optical spectra [51-54].

### 1. 1. 3 An optically smart antenna array

We chose to demonstrate the potential merit of the autotuning filter in a communications scenario. More specifically, the filter was incorporated in the adaptive optical processor of signals received by a microwave antenna array. Adaptive processing in smart antenna systems [55, 56] can either be done at the analog front-end at the carrier frequency or after down conversion and analog-to-digital conversion at base-band using digital signal processing (DSP) techniques [57]. Front-end processing is fast, but expensive and complex as the adaptation circuitry requires microwave variable phase-shifters and variable gain-control elements. The more common DSP approach reduces system complexity, is more economical, and more flexible; however, it is typically power inefficient and has modest bandwidth. Part of this thesis's goal is to show that the use of photorefractive circuitry can simplify adaptive antenna systems and relieve the computational burden placed on the digital signal processing done after down conversion.

Principal component extraction on antenna array signals subscribes to the broad field of blind source separation (BSS) [58, 59]. This field seeks to separate unknown mixtures of unknown signals that possibly have overlapping bandwidths. The less assumptions a blind separation method makes about the unknown signals, the more powerful it is. For principal component separation to function as a BSS method [59], the unknown signals have to be received in temporally and spatially orthogonal mixtures. The temporal orthogonality or non-correlation is guaranteed in most communications scenarios by the fact that the signals are emitted from independent sources. The spatial orthogonality is a more restrictive condition. However, as will be shown in Chapter 3, principal component separation as a BSS method works only as well as the signals are spatially uncorrelated. The signals are 100% spatially

correlated only when they are emitted from the same spatial location (within the receiving antenna's angular resolution.)

The architecture of the processing system discussed in this report is intended to be used in applications with a large number of antenna elements. The experimental demonstration uses only two microwave receivers and two test sources; however, the optical processor does not substantially change as the number of array elements increases. The prototype system is illustrated in Figure 1.2.

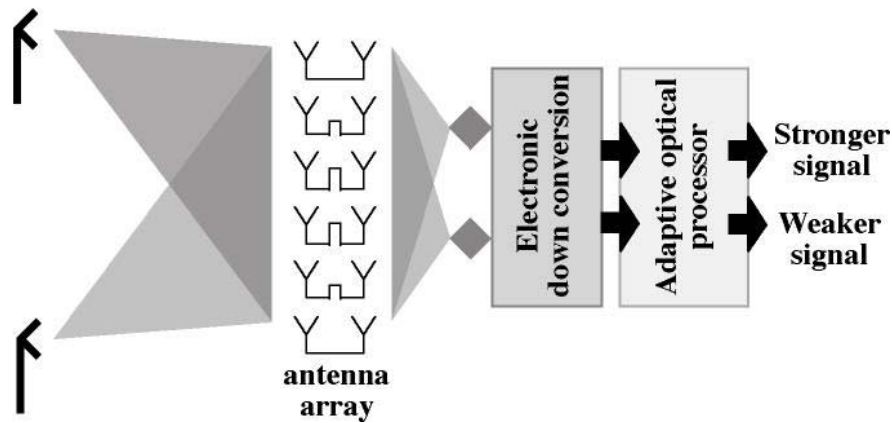


Figure 1.2. Block diagram of the prototype optically smart antenna array.

The first stage of our prototype system receives two 10 GHz signals from two distinct sources placed in the far field of the array. Audio signals amplitude-modulate the microwaves. The receiving front end consists of a 30-element antenna array that acts as a quasi-optical discrete lens [60] with detecting antennas placed on its focal arc. The two electrical signals from the detectors are then down converted to 150 MHz and amplified before being fed to the second stage of the system. The IF signals are applied to a one crystal, two-channel resonant electro-optic phase modulator. An optical line beam traverses the electro-optic modulator with its top half modulated with one of the IF signals and the bottom half modulated with the other. Since this is phase modulation with low modulation

indices, the original optical frequency is still present in the beam, necessitating a carrier suppression element in order for the autotuning filter to work properly. If the carrier is not suppressed it introduces artificial correlation between the signals that impairs the proper functioning of the filter. The suppression of the carrier is achieved by two-beam coupling the signal-bearing beam with a non signal-bearing beam. The photorefractive crystal is oriented such that the beam carrying information transfers energy to the non-modulated beam. Although the signals suffer a 3dB loss in the process, the carrier frequency is suppressed by over 50 dB. The final processing stage consists of the autotuning filter. It extracts the principal component of its two-dimensional input signal space. The oscillating beam of the filter is sampled and photodetected. Detection without homodyning is possible because the absence of the optical carrier turns the phase modulation into an amplitude modulation at twice the frequency. Demodulating electronics retrieve the audio signal from the AC port of the photodetector and send it to a speaker.

The whole system from the down conversion stage to the electronic output is packaged in a 13x18x6 inch briefcase. It plugs into a wall outlet consuming power equivalent to a common household light bulb. The briefcase system has proven its robustness and portability by demonstrating real-time principal component extraction around the country. The miniaturization and packaging of optics including interferometric setups in a briefcase is a significant accomplishment in and of itself. It shows that optical table-size systems (4x6 feet) may be considerably shrunk in size and made to work without the cumbersome vibration isolation offered by air-cushioned tables.

#### 1. 1. 4 A photorefractive regenerative amplifier

Multiple stage electronic circuits require amplifier modules within or in between stages. The art and science of making amplifiers is a sophisticated branch of electronics. Sub-branches include high power amplifiers and low noise figure amplifiers, the design skills of which vary immensely depending on the operational frequency range. As our photorefractive systems grow in size and complexity, laser power becomes an issue. Barium titanate crystals generally have a high absorption constant—a typical  $\alpha$  is between 1 and 2  $\text{cm}^{-1}$  (for green wavelengths.) Taking the autotuning filter as a familiar example, this means that the through beam carrying all but the largest principal signal loses about half its energy passing through the “gain medium” of the ring (our crystals are typically around 5 mm in length.) Without an amplifier, the initial power of the beam determines how much more processing can be applied to it.

Optical regenerative amplification is a young field compared to its electronic counterpart [61]. The field blossomed in the early 1990’s when optics were massively introduced in telecommunication systems. Optical amplifiers are, still today, developed mainly for the purposes of the communications industry. The operating wavelengths of the vast majority of these devices are therefore closely matched to the 1.3 and 1.5  $\mu\text{m}$  communication wavelengths. Industrial research also focuses on single spatial mode amplifiers; again, because optical communication systems employ single mode fibers to propagate their beams. Unfortunately there are no efficient photorefractive materials at communication wavelengths. Barium titanate works best with blue and green wavelengths and rhodium doping extends its operating range to the visible red. Other photorefractive materials function for wavelengths up to 1.06  $\mu\text{m}$  although their coupling constants  $\Gamma$  are not as high. In addition, the dynamics

of our photorefractive circuits require the spatial diversity of multi-mode beams. These facts prompted us to develop our own amplifiers.

The basic concept of a regenerative optical amplifier is relatively simple. Stimulated emission amplifies an optical information-carrying beam propagating through a population-inverted medium. The latter may be the same gain medium as the one used in the laser that originally generated the beam: the gain bandwidths of these materials generally cover thousands of gigahertz. A high noise figure constitutes the main drawback of non-parametric, i.e. simple, traveling wave amplifiers. The theoretical minimum decrease of the signal to noise ratio is 3 dB. A high number compared to low noise electronic amplifiers that limits the number of times a signal may be amplified before it drowns in noise.

The amplifier design presented in this thesis takes a multi-mode beam in and outputs an amplified single mode beam without any loss of temporal information. Like the autotuning filter it is essentially a photorefractive oscillator. A photorefractive element also couples the input to the oscillating beam. Unlike the autotuning filter, a semi-conductor laser diode amplifier provides gain to the loop and washes out the competition for photorefractive gain. The resonator is constrained to be single mode, which allows the use of a single mode semi-conductor amplifier in the ring. The oscillating beam picks up all the temporal information of the multi-mode input beam, since there is no competition for gain. The photorefractive gratings have no reason to organize themselves so as to select one part of the information over another. This oscillator thus transforms a multi-mode beam into a single mode with more energy.

This thesis reports the first steps toward making the amplifier. The semiconductor laser diode amplifier for red wavelengths was assembled in the laboratory, starting with uncoated chips. Another necessary experiment for demonstrating the feasibility of our photorefractive amplifier involved showing that a multi-mode beam could pump a resonant cavity that was forced to be single mode. This amplifier will hopefully be the first of a series. Our toolbox

of photorefractive circuits would be greatly enriched by the development of high performance semi-conductor amplifiers at red wavelengths. The privilege of that work though, is left for other graduate students. ☺

## 1.2 Thesis outline

This thesis reports work on three separate projects. Chapter 2 presents the experimental and theoretical progress in relation to the autotuning filter. Chapter 3 describes the making of an opto-electronic microwave processor and evaluates its performance. Chapter 4 reports on preliminary research for a photorefractive regenerative amplifier. The fifth and last chapter (the appendix) regroups supplementary technical information relative to various sections from the previous chapters.

Chapter 2 is divided into three sections. The first section aims to present the reader with an intuitive understanding of the autotuning filter's functioning. This short section offers enough information to make sense of the experimental section and provides a background for the discussions in the theoretical section. The second, experimental section describes the different implementation trials of the autotuning filter and discusses their performances. The third, theoretical section is divided into three parts. The first part studies the influence of the filter's parameters on its signal separation performance. The second part compares the experimental filter's data with a mathematically pure principal component extractor. The third part demonstrates the principal component extraction ability of the filter starting with the photorefractive differential equations embodying its design.

Chapter 3 describes in details the design, operation and measured performance of the adaptive microwave receiver. It consists of three major components: the microwave front end, the electro-optic modulation and carrier suppression stage, and the optical processing (auto-tuning filter) stage. A separate section explains each stage and reveals the packaging efforts that enabled to fit the system in a 13x18x6 inch briefcase. The result section reports the signal separation performance of the suitcase from a system's point of view. The last section of the chapter discusses the implementation of an extension of the 2-receiver system

to an N-receiver adaptive array, and the implications of using an optically smart quasi-optical antenna array in radar and communications.

Chapter 4 discusses the design of a photorefractive regenerative amplifier. It also reports on the experimental procedure to build a semiconductor laser diode amplifier necessary for the implementation of the photorefractive amplifier. The procedure described starts out with an uncoated and unmounted InGaAlP chip. The appendices present the detailed designs of some mechanical systems that we found particularly useful in the realization of the work presented in Chapters 2 and 3. They include practical information relating to the manufacturing of BaTiO<sub>3</sub> spheres and an operating manual for the suitcase system. The appendix also provides the Mathematica codes for the numerical simulation and study of the autotuning filter.

### 1.3 Contributors to this thesis

The design of the autotuning filter was first presented in 1991 as a frequency demultiplexer [10]. This thesis introduces the building and testing of experimental versions of the filter as a principal component extractor. The influences of the filter's parameters on the device's signal separation performance were studied with a Mathematica program (presented in the appendices) that was greatly enhanced through discussions with Dr. A. Zozulya. His work on the stability analysis of a photorefractive feature extractor [62] allowed the demonstration of the autotuning filter's principal component extraction abilities in Chapter 2.

The realization of the suitcase project (Chapter 3) was the product of teamwork among Dr. S. Romisch and graduate student P. Smith, advised by Professor Z. Popovic, and myself. Dr. S. Romisch and P. Smith designed and built the front-end's electronics. I designed, machined and packaged the optical stage of the system. Dr. S. Romisch designed and built the demodulation electronics after the optical stage. Later, J.H. Loui helped me improve their performance. Dr. S. Romisch, P. Smith and I tested the different parts of the suitcase project and took the characterizing end-to-end measurements of the system. Professor D.Z. Anderson and Professor Z. Popovic contributed heavily to the discussion of the system from a communications perspective. The 4-channel implementation of Professor D.Z. Anderson's multiple-channel EOM idea, was designed, built and tested by graduate student H. Matern, advised by Professor Z. Popovic and experimentally assisted by myself.

My experimental work on assembling a semiconductor amplifier in Chapter 4, was guided by Dr. L. Hollberg. N. Mackie, a member of Dr. L. Hollberg's group, supervised and assisted my anti-reflection coating trials. Graduate student S. Hugh built the single mode cavity pumped by a multi-mode beam via a photorefractive crystal.