# ALL-OPTICAL MICROWAVE FRONT END FOR SDR

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## ABSTRACT

To fully realize its promise of an all-encompassing communications device, special attention must now be given to the radio frequency (RF) front end of Software Defined Radio (SDR). While much work has been done to enable most air interfaces to be digitally implemented on signal processors, SDR's still use conventional RF designs for their front end, and thus can only operate over limited frequency ranges. The ideal SDR RF unit would be frequency-agile, tunable and could be incorporated directly into a radio to replace multiple banks of microwave sources, thus reducing the size, weight and (ideally) cost of the unit. This is a daunting task in the electrical domain and a paradigm shift may be in order.

In this paper, progress made towards the development of a high-quality, optically-generated SDR transceiver is presented. Microwave source designs, capable of generating a carrier tunable to more than 50 GHz, will be detailed along with techniques for RF filtering in the optical domain. The initial steps towards the design of a photonic integrated circuit (PIC), which combines the different components required to make an optical device feasible in a SDR, will also be presented.

## 1. INTRODUCTION

SDR technology has made significant advancement over the past decade. From the Speak-Easy radio to the Joint Tactical Radio System (JTRS) program, the technology has moved from demonstrator to field deployable units. Most of the evolution, however, has been made on the signal processing side of the radio. Faster and larger processors, faster analog-digital converters, more efficient signal-processing algorithms and improved digital hardware architectures have focused most of the attention.

If SDR is to fully realize its promise of an all-encompassing radio, covering a variety of air interfaces over multiple frequency bands, special attention to the radio frequency (RF) front end is now required. While almost any waveform or air interface can be emulated digitally, current radio implementations are still limited by the frequency range over which they can operate. The initial JTRS program limited the applicability of SDR to frequency bands below 2 GHz. The requirement has now shifted to cover applications supported by satellites or terrestrial broadband wireless services operating up to 60 GHz. Although SDR can be implemented below 6 GHz using conventional electronics, it is increasingly difficult to do so at the higher operating frequencies. Moreover, the ideal microwave source needs to be frequency-agile, tunable over a wide range of frequencies and could be incorporated directly into a radio to replace multiple banks of conventional microwave sources, thus reducing the size, weight and ideally cost of the unit. This is a daunting task in the electrical domain and a paradigm shift may be in order.

Optical technology can emulate many of the functions normally seen in electronic circuits and is an ideal candidate to perform many of the tasks described above. Optical heterodyning (a process similar to RF mixing where two optical signals of different wavelengths are beat on a photodetector in order to generate a microwave signal) is an appealing technique to generate microwave signals over a very large frequency range - from MHz to THz. However, the primary difficulty in generating a high-quality signal with this approach is the need to narrow the inherent linewidth of semiconductor lasers (typically a MHz) down to values more practical for a communications system.

In this paper we will review a few approaches being investigated by Communications Research Centre and its collaborators towards the development of a high-quality, optically-generated SDR transceiver. It is our intention to show that all of the elements traditionally associated with RF reception and transmission can be reproduced optically. Microwave source designs based on non-linear up-conversion, dual frequency lasers and optical phase-locked loops (OPLL's) will be detailed. The former has been experimentally shown to generate a microwave carrier tunable up to more than 50 GHz using off-the-shelf components. Techniques for RF filtering in the optical domain will also be examined. Optical amplifiers, a common commercial component, will be briefly mentioned. Finally the significance of photonic integration to the practical implementation of SDR will be discussed.

 

## 2. OPTICAL RF IMPLEMENTATION

### 2.1 Source Development

Optical generation of microwave signals by heterodyning the outputs of two narrow-linewidth lasers has been demonstrated numerous times in the past [1]. With this optical approach, the electrical RF signal results from the beating of two optical waves, separated by the desired mm-wave frequency, on a square-law photodetector. If the frequency difference of the two optical signals were stable and their phases correlated, the generated electrical signal would have a narrow linewidth and stable center frequency - a requirement for most system applications. However, in most approaches the beat signal produced usually possesses a linewidth that is comparable to the sum of the optical linewidths, typically a few MHz for semiconductor lasers. This is because the phase noise of the two laser sources is not correlated in any way. As such, the instantaneous frequency difference can vary by the extreme low end of one laser spectral distribution to the high end of the other. If the phase difference between the two lasers were to be highly correlated then a very narrow RF linewidth could be achieved even with large linewidth optical sources. Three implementations, all of which use off-the-shelf components, are suggested to reduce the linewidth of the beat signal.

*2.1.1 Non-linear Optical Modulator*

One way to ensure that the phase correlation between the two optical carriers is identical is to use a single laser to generate both. This can be done by relying on the inherently non-linear response of an electro-optic modulator, which allows both carrier generation and harmonically-generated frequency up-conversion [2]. Taking advantage of the up-conversion aspect can dramatically lower the electrical requirements for the modulator drive signal.

Using this technique we have demonstrated a simple approach to optically generate continuously-tunable, microwave and mm-wave signals. The proposed system consists of a commercially available 10-Gbps electro-optic intensity modulator driven by an RF signal. The intensity modulator is biased at a DC voltage adjusted so that odd-order optical sidebands are suppressed. A fiber Bragg grating (FBG) is employed to filter out the optical carrier, which is at the wavelength of the optical source feeding the modulator. As such, the only significant remaining optical components are the two second-order sidebands. Beating these harmonics at a photo-detector generates a four-time unconverted electrical signal. A tunable, low-phase noise, mm-wave signal that ranges from 32 GHz to 60 GHz is generated when the reference microwave source is tuned from 8 GHz to 15 GHz.

Figure 1 illustrates the experimental setup used for testing the source, while Figure 2 shows the electrical spectra of a 50-GHz mm-wave signal generated with a microwave drive signal at 12.5 GHz. The solid line shows the drive signal, while the dashed-line shows the signal at the output of the photodetector. Note that even though the laser linewidth is on the order of a MHz, the linewidth of the optically-generated 50 GHz signal is only limited by that of the 12.5 GHz drive signal, see Figure 2. The primary difficulty with this design is the poor conversion efficiency.

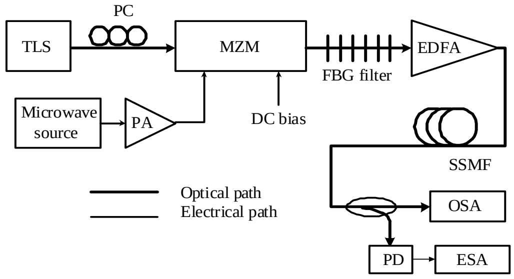


Figure 1: Experimental setup for optical generation mm-wave signals using the non-linearity of an optical modulator (TLS: tunable laser source, MZM: Mach-Zehnder modulator, EDFA: erbium-doped fiber amplifier, PA: power amplifier, OSA: optical spectrum analyzer, PD: photo-detector, ESA: electrical spectrum analyzer, SSMF: standard single mode fiber).

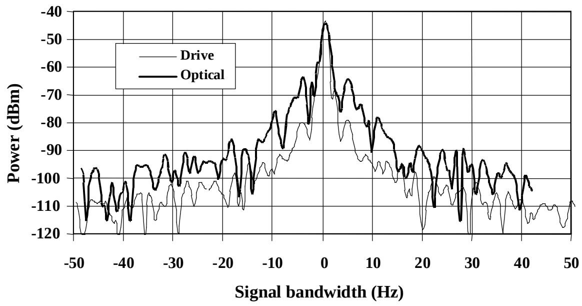


Figure 2: Comparison of the optically-generated 50 GHz signal (optical signal) to the 12.5 GHz electrical drive signal. Note that center frequencies have been normalized to allow comparison of the linewidths.

*2.1.2 Optical phase-lock loop (PLL)*

A second approach to microwave source design is based on a discriminator-aided, PLL [3, 4]. The discriminator is used to maintain the frequency separation between the two lasers within the relatively narrow capture range of the PLL. This essentially finds the right operating frequency and coarsely locks on it. The PLL can then be used to reduce the linewidth of the microwave output to a value suitable for communications system applications.

Both the frequency discriminator and the PLL are forms of electronic feedback that compare the output beat signal to a microwave reference, and then feed a correction signal back to one of the lasers. The design retained for this project was similar to the one proposed in [3], but all the electronics and the external-cavity lasers (ECL) used in the construction are commercially available. A schematic diagram of the design is shown in Figure 3.

 

The outputs of the master and slave lasers are optically mixed and allowed to beat on two photodetectors. The output of one photodetector is amplified and used as the RF/microwave output signal. The output of the second is used to provide feedback for the discriminator/PLL.

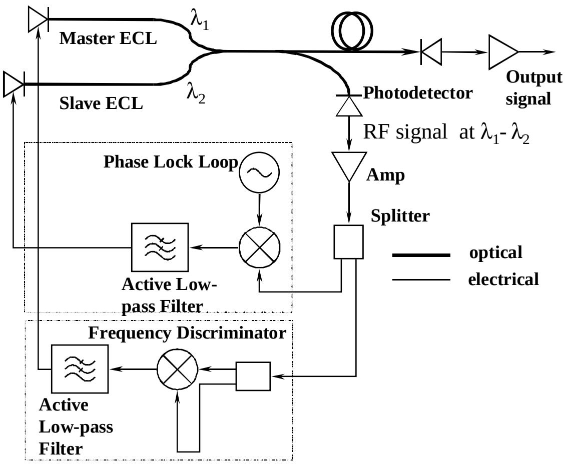


Figure 3: Schematic diagram for the optical PLL.

The purpose of the discriminator is to minimize the variation in frequency difference between the master and slave laser, thereby producing a stable microwave output signal. It does this by comparing the beat signal to a fixed reference, generating a DC correction signal based on the difference between these two. This comparison can be done in a number of ways, but the technique employed in this project is the use a microwave delay line. The correction signal is then passed through an active, low-pass filter and injected into one of the lasers to vary its operating wavelength. Once the active, low-pass filter and laser responses have been measured, then the feedback levels for proper discriminator operation can be established.

After establishing the coarse lock, then the linewidth can be reduced by the PLL. This portion of the circuit consists of a voltage-controlled oscillator (which in our case is the laser), a phase detector (mixer), and a low-pass filter. Both passive and active loop filters are widely used in PLL design. The passive filter is simple to implement and is satisfactory for many applications, but an active loop may provide better tracking performance. The primary disadvantage of the active loop is the additional propagation delay, a detrimental parameter, introduced by the high-gain DC amplifier. The applied results of the PLL are shown in Figure 4.

*2.1.3 Dual-frequency External Cavity Laser (ECL)*

Rather than using two independent lasers, efforts have been made to produce a dual-wavelength ECL. In such a laser, two wavelengths are allowed to co-exist. This is done by fabricating a device with one common gain medium, but with two concentric cavities, see Figure 5. Such a device may be able to take advantage of the potential noise correlation between adjacent modes [5]. However, due to the gain competition and the large threshold gain sensitivity, a dual-wavelength ECL may exhibit mode switching, especially when the two lasing wavelengths are closely spaced. Although polarization separation techniques have been proven to be very effective in stabilizing two closely-spaced modes [6], they usually require free-space polarization controlling devices, which make the integration a non-trivial task.

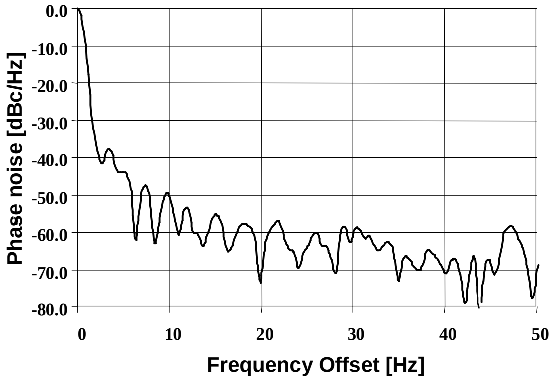


Figure 4: Optical PLL phase noise at an operating frequency of 11.224 GHz.

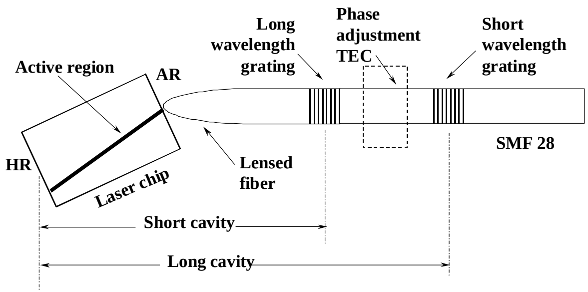


Figure 5: Schematic representation of the ECL. The laser chip has a high-reflectivity (HR) coating on one facet and an anti-reflection (AR) coating on the other. Each grating forms a cavity in the lensed fiber, with a phase adjustment section between them.

We have experimentally demonstrated that two closely spaced lasing wavelengths can co-exist for short periods, even without the assistance of a polarization separation technique [6], see Figure 6. However, when the two wavelengths are closely spaced (~0.3 nm), optical gain competition can suppress one of the two lasing wavelengths, and a slight change in the cavity can cause the longitudinal lasing mode to switch. In addition, we experimentally verified that the external optical feedback at both lasing wavelengths must satisfy an in-phase relation with the residual feedback from, for example, the gain chip facet in order to obtain a true dual-single-mode emission.

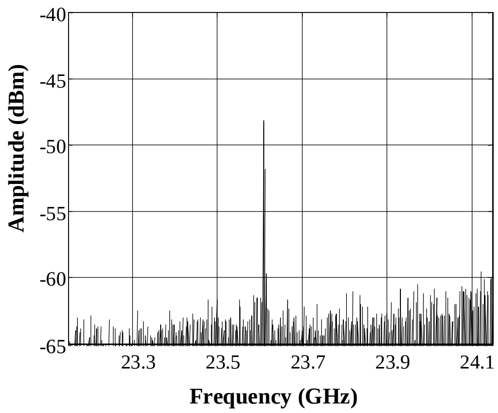


Figure 6: Microwave output of the dual-frequency ECL

## 2.2 Tunable all-optical microwave filters

The previous section clearly establishes that a microwave signal can be generated in the optical domain for RF/IF frequency translation. In addition, the square-law response of a photodetector effectively acts as a mixer. The next component addressed in the optical RF design is a filter.

All-optical microwave filters proposed in the past few years were primarily based on incoherent manipulation of optical carriers with only positive taps [7]. As such, only low-pass filtering functionality could be realized. For many applications, such as SDR systems, bandpass and flattop filters are required. To overcome this limitation, several techniques have been proposed.

Recently, Yao et. al. [7] reported a method for implementing an all-optical microwave bandpass filter with a simple structure. The baseband resonance of this typical low-pass filter is eliminated by using an electro-optic phase modulator (EOPM) combined with a dispersive device. Yao et. al. [8] also proposed a novel method for realizing an all-optical microwave bandpass filter with negative coefficients. Positive and negative coefficients are obtained through PM–IM conversion by reflecting the phase-modulated optical carriers from linearly chirped fiber Bragg gratings (LCFBG's) with positive or negative dispersions.

The fundamental concept is shown in Figure 7. Under small signal modulation conditions, the phase-modulated optical spectrum is illustrated on the left side of the figure, which consists of an optical carrier ($\omega_o$) and two first-order sidebands ($\omega_o+\omega_m$, $\omega_o-\omega_m$ where $\omega_m$ represents the modulating microwave frequency). At the output of the phase modulator, the two sidebands are $\pi$ out of phase. If the phase-modulated signal is directly detected with a photodetector (PD), the modulating signal cannot be recovered, and only a DC signal is observed because beating between the carrier and the upper sideband exactly cancels the beating between the carrier and the lower sideband. However, as shown in Figure 7, if the modulated optical signal passes through a dispersive device, the phase relationship between any two optical frequency components will change due to chromatic dispersion. When this dispersed optical signal is fed to a photodetector, the modulating signal can be recovered, which implies that the PM is converted to IM by the dispersive device. More interestingly, when D>0 (the upper case in Figure 7), the higher optical frequency component experiences more phase shift than that of the lower frequency component, and eventually the PM–IM conversion is fully achieved when all three frequency components are exactly in phase. On the contrary, when D<0 (the lower case in Figure 7), the lower frequency component will experience more phase shift than the higher one, and the PM–IM conversion is fully obtained when the two sidebands have the same phase but are $\pi$ out of phase with the carrier. Consequently, the recovered RF signals from the different dispersive devices will have a $\pi$ phase inversion, which can be directly applied to implement negative coefficients in an all-optical microwave filter.

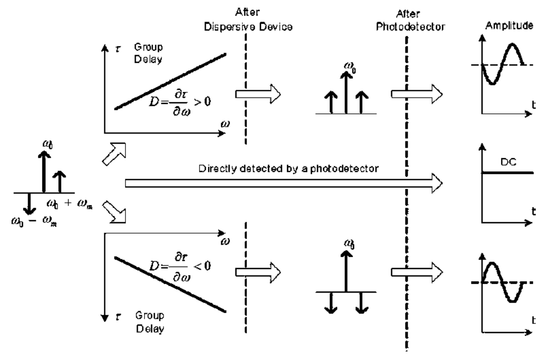


Figure 7: Illustration of the recovered RF modulating signals that sustain a positive, zero, or negative chromatic dispersion.

From the analysis above, a basic architecture for the proposed filter is presented in Figure 8. Optical carriers from an array of N laser diodes (LDs) emitting at $\lambda_1$, $\lambda_2$ … $\lambda_N$ are combined via an optical combiner and applied to a phase modulator. Through an optical circulator, the modulated optical signals are demultiplexed by an arrayed waveguide grating (AWG) and fed to N LCFBG's via either the short-wavelength or the long-wavelength port, depending on whether the LCFBG's are employed to implement positive or negative taps. The reflected and dispersed optical signals are then multiplexed by the same AWG and sent to a photodetector to recover the modulating RF signal. The recovered RF signal can be expressed as a vector summation of the resulting electrical signals from the N carriers. The length difference between the optical paths determines the central frequency of the pass band. Therefore, by altering the laser wavelengths then the filter response can be tuned.

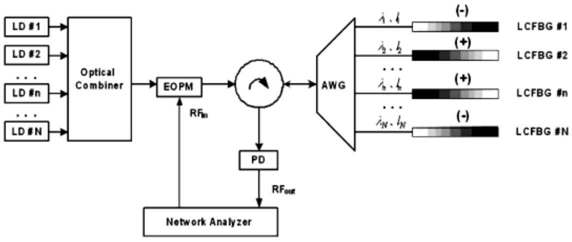


Figure 8: Basic architecture for the proposed optical RF filter.

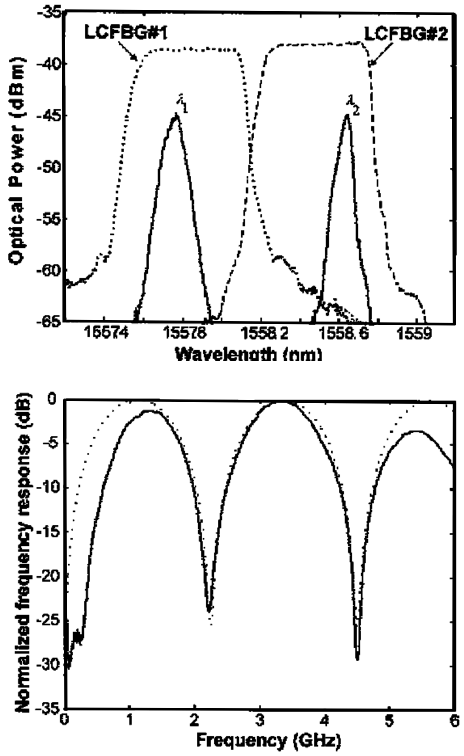


Figure 9: Experimental results of the two-tap filter with one negative coefficient. (a) Measured optical spectrum (solid curve) when $\lambda_1$ is reflected by LCFBG#1 from the short wavelength port and $\lambda_2$ is reflected by LCFBG#2 from the long-wavelength port. (b) Frequency responses: measured (solid curve) and simulated (dotted curve), showing a bandpass filtering with one negative tap.

To prove the above concept, a two-tap microwave filter with one negative coefficient was implemented. Two LCFBG's are fabricated with a central wavelength shift of 0.7 nm. Both gratings (LCFBG#1 and LCFBG#2) have a length of 8 cm and the average dispersions are calculated to be 1350 and −1327 ps/ nm, respectively. Two tunable LD's, emitting at $\lambda_1$ and $\lambda_2$ with identical output power levels and a typical linewidth of 150 kHz, are applied as the light sources.

In summary, the optical RF filter has a simple structure with positive or negative coefficients obtained through PM–IM conversion by reflecting the phase-modulated optical carriers from the regular LCFBG's with positive or negative GD slopes. A two-tap microwave bandpass filter with one negative tap was demonstrated, it has a better main-to-sidelobe ratio (MSR) compared to the bandpass-equivalent filter with all-positive taps. More taps with either positive or negative weights can be easily realized by simply adding more LCFBG's, which provides the possibility of implementing microwave bandpass filters with a flat-top response and a high MSR.

### 2.3 Optical Amplifiers

Finally, an optical transceiver would not be complete without an amplifier. Optical amplifiers use a short length of optical fiber doped with the rare-earth element erbium as a gain medium. Also called an erbium-doped fiber amplifier (EDFA), they act as optical or IR repeaters that boost the intensity of a modulated laser beam directly, without opto-electronic/electro-optical conversion. The EDFA uses a semiconductor pump laser to introduce a powerful beam at a shorter wavelength, typically 980 nm or 1480 nm, into a section of doped fiber a few meters long. The pump light excites the erbium atoms to higher orbits, and the 1550 nm input signal stimulates them to release excess energy as coherent photons at the same wavelength. EDFA's are commonly used in long-range optical fiber communications systems to compensate for the loss of long fiber spans.

## 3. PHOTONIC INTEGRATION

Monolithic integration provides a means for combining multiple functions and devices onto a single chip, enabling significant reduction in cost, footprint and power, while at the same time improving overall reliability and performance. Photonic integrated circuits (PIC's) are the monolithic integration of two or more optical elements on a single substrate. They are the photonic equivalent of electronic integrated circuits, however, instead of guiding current, a photonic integrated circuit guides light. Like in the microelectronics industry, photonic integration will give rise to vastly improved functionality, reduced costs and improved reliability.

Until recently, factors such as high propagation loss, material limitations and the absence of a large end-market made it difficult to justify the capital expenditures required to implement the integration process. However, with a renewed interest in high-volume, low-cost components for the metro market, together with recent advances in material structures and device layouts, the situation appears to be changing.

Monolithic integration of optical components offers many advantages over assemblies of discrete components and is the key to any future deployment of optics in SDR. Since the introduction of PIC's in the mid 1990's, the optical component industry has slowly been migrating from the manual assembly of discrete optical devices to automated, semiconductor wafer-processing techniques and single-chip solutions. The material systems of choice for monolithic integration are InP and InGaAsP, which allow the design of both the active and passive waveguides for operation in the spectral ranges of interest.

In the past, we have adopted a building block approach to system design both in optical RF circuit design and in the development of integrated components. While the various RF elements described above have been developed and optimized using discrete off-the-shelf components, work has been done in parallel on optimizing the fabrication process required to construct monolithic versions of these circuits [9]. Typical examples are shown in Figure 10, which displays both a laser and waveguide grating developed at Sherbrooke University. Work continues on the integrating of the various elements.

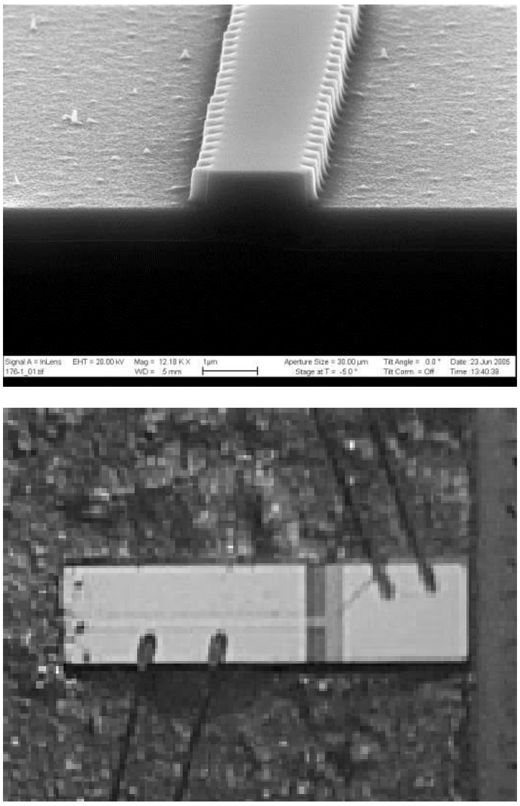

Figure 10: Elements of a photonic integrate circuit; the top image is a first-order grating etched in a waveguide, while the lower image is laser monolithically integrated with an electro-absorption modulator using Quantum Well Intermixing [9].

In conclusion, we have provided a brief overview of the various elements required for an optically-generated SDR transceiver. Optical technology can emulate several of the functions normally seen in electronic circuits and, in many cases, can provide much greater versatility in doing so. For example, optics-based sources can easily generate carriers with up to THz frequencies. As photonic integration progresses, this technology will be more prevalent in everyday applications. Communications Research Centre and its collaborators will continue their team approach to complete an all-optical microwave front end for SDR.

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# All-Optical Microwave Front End for SDR

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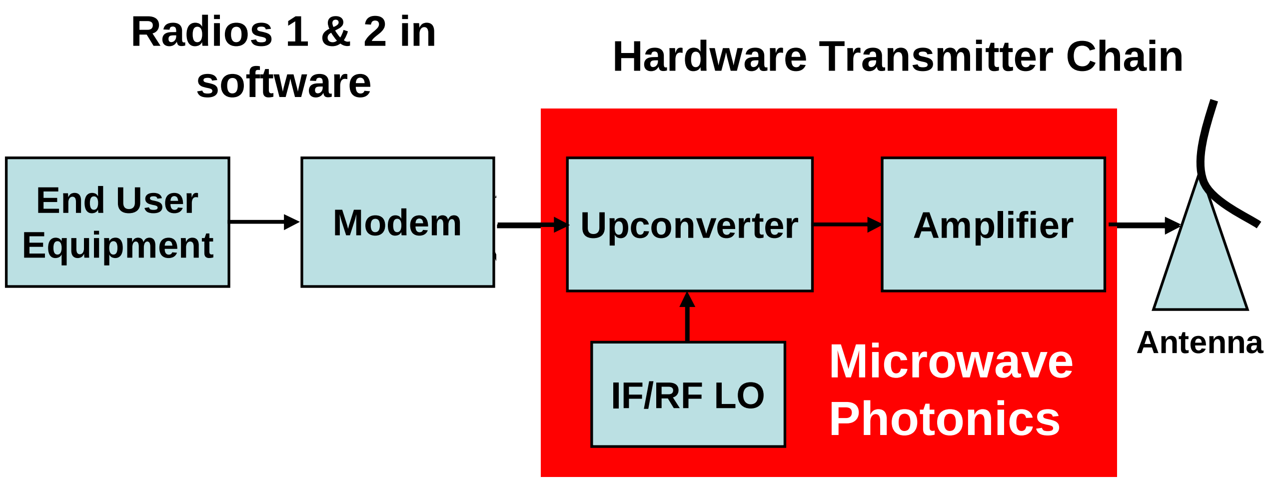
CRC

# CRC Radio Systems Overview

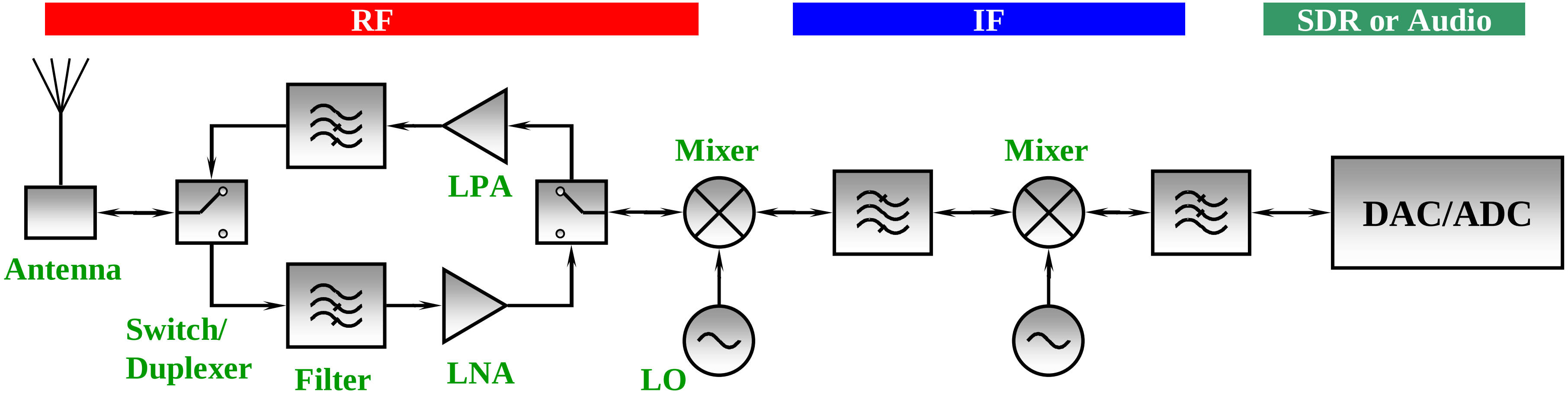


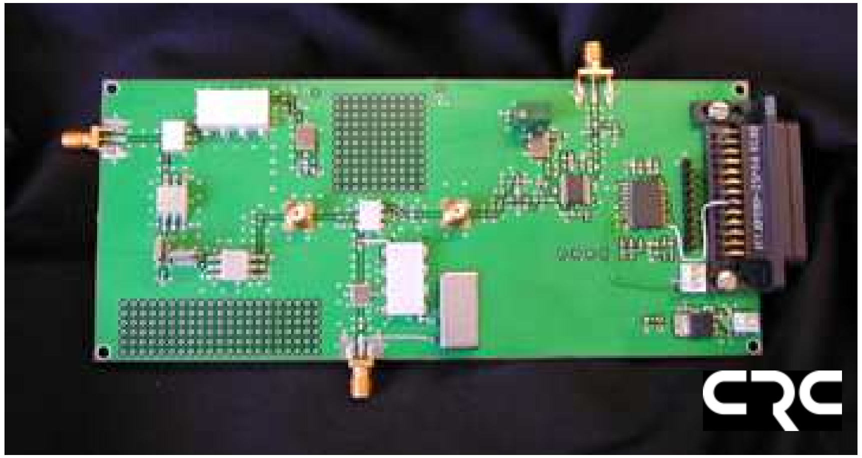
CRC's 50 years of experience covers every aspect of radio design from propagation, modelling, signal processing, hardware all the way to field trials.

# Microwave Photonics in Software Defined Radio



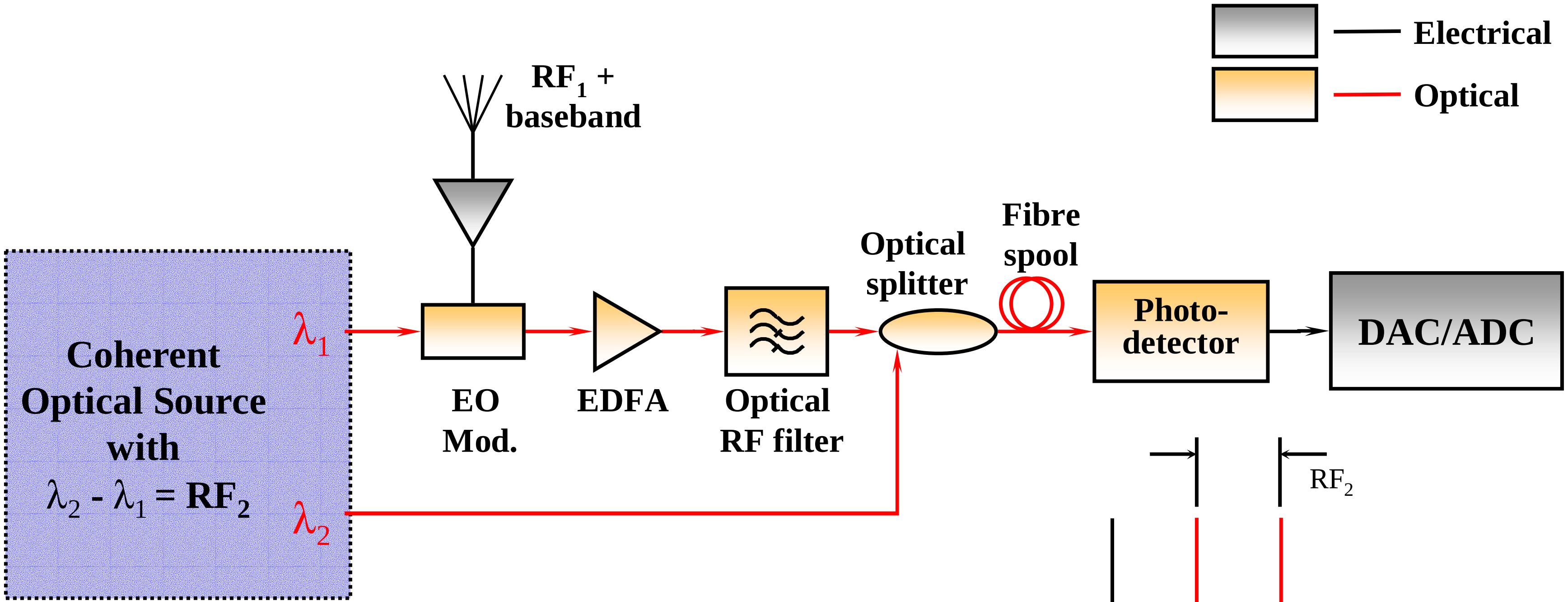
# Conventional Radio Electronics

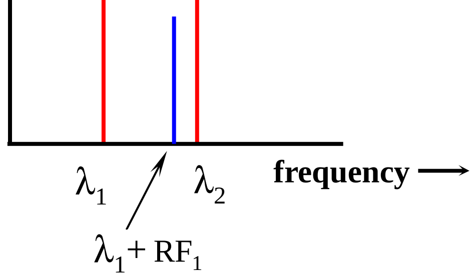


# Proposed Optical SDR Receiver





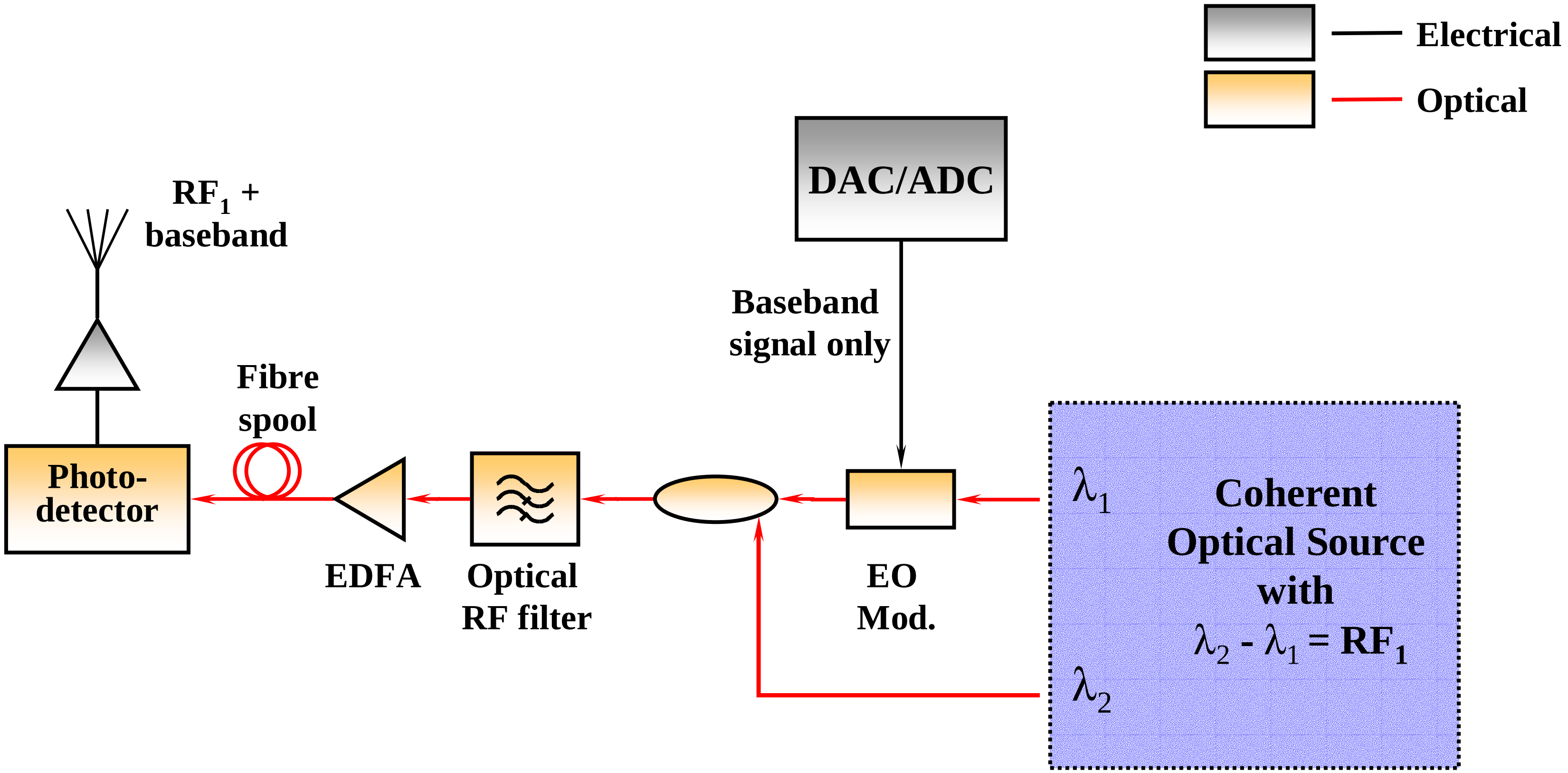




**Advantages of an optical system**

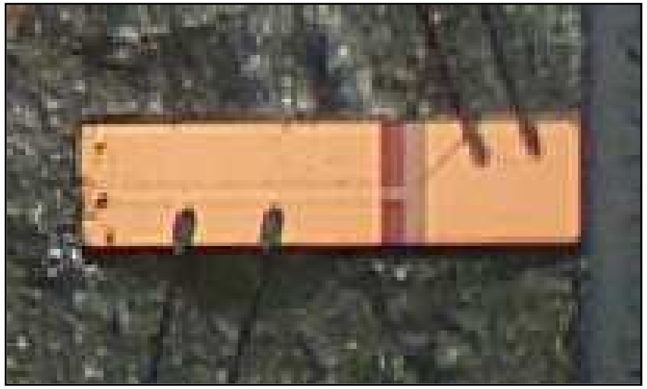
- EMI/Signal integrity
- remote distribution
- large operating frequency range (~1-100's GHz)

**Output signal:**
**Modulated by both optical beat signal at $\lambda_2 - \lambda_1 = RF_2$, and antenna $RF_1$. Difference frequency will be a RF2-$RF_1$**

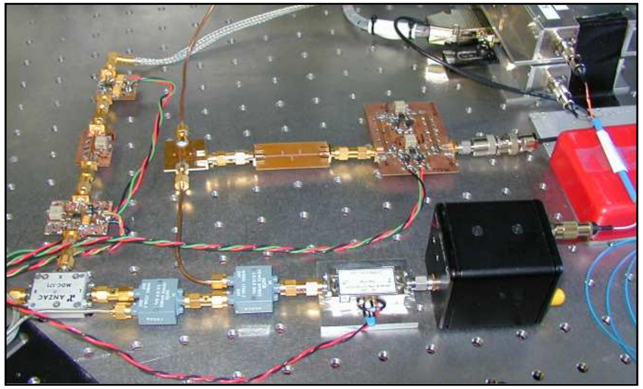
# Proposed Optical SDR Transmitter



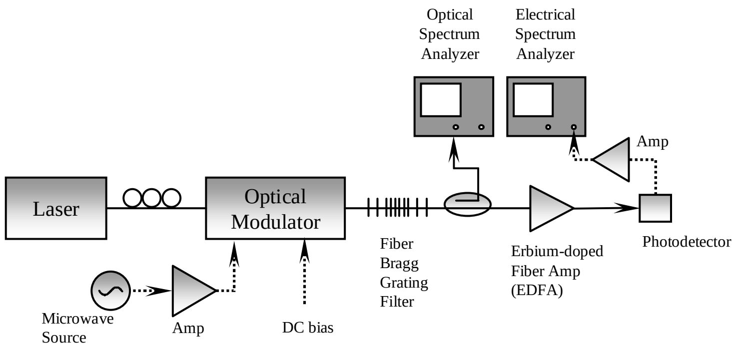
# Source Summary



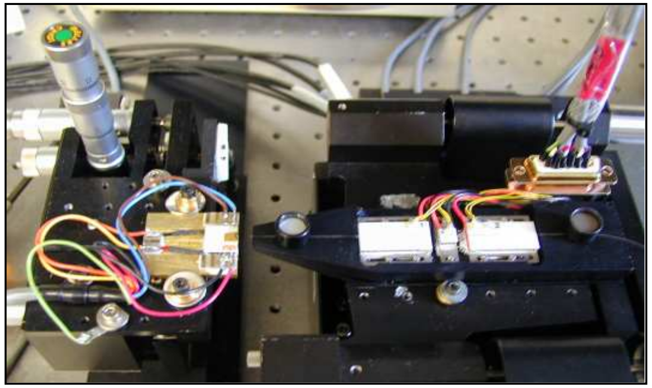
**Mode-Locked Laser**



**Optical PLL**



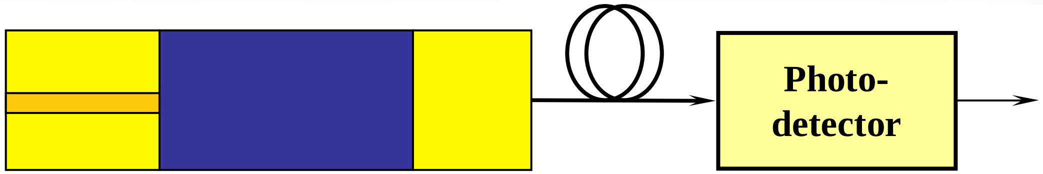

**Single-Laser Heterodyne**

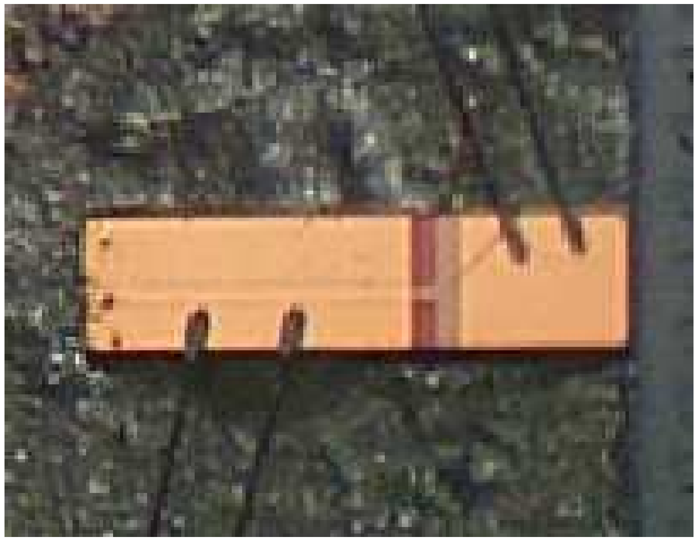


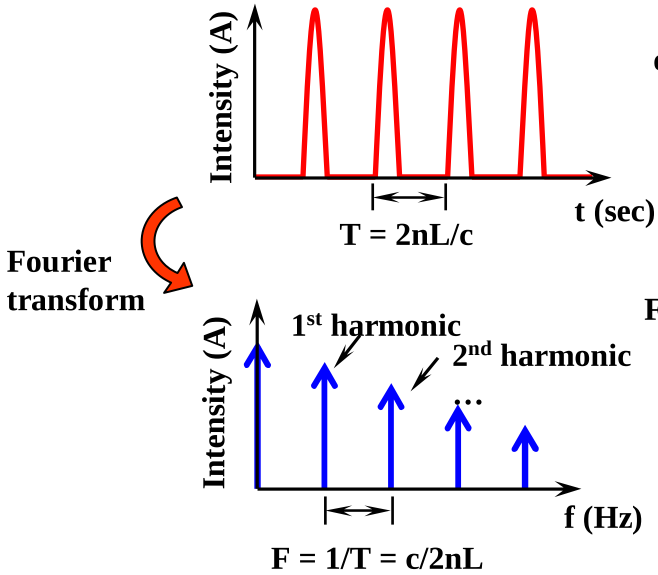
**Dual-wavelength ECL**

# Mode-Locked Laser

**Pulsed Laser transmitter**



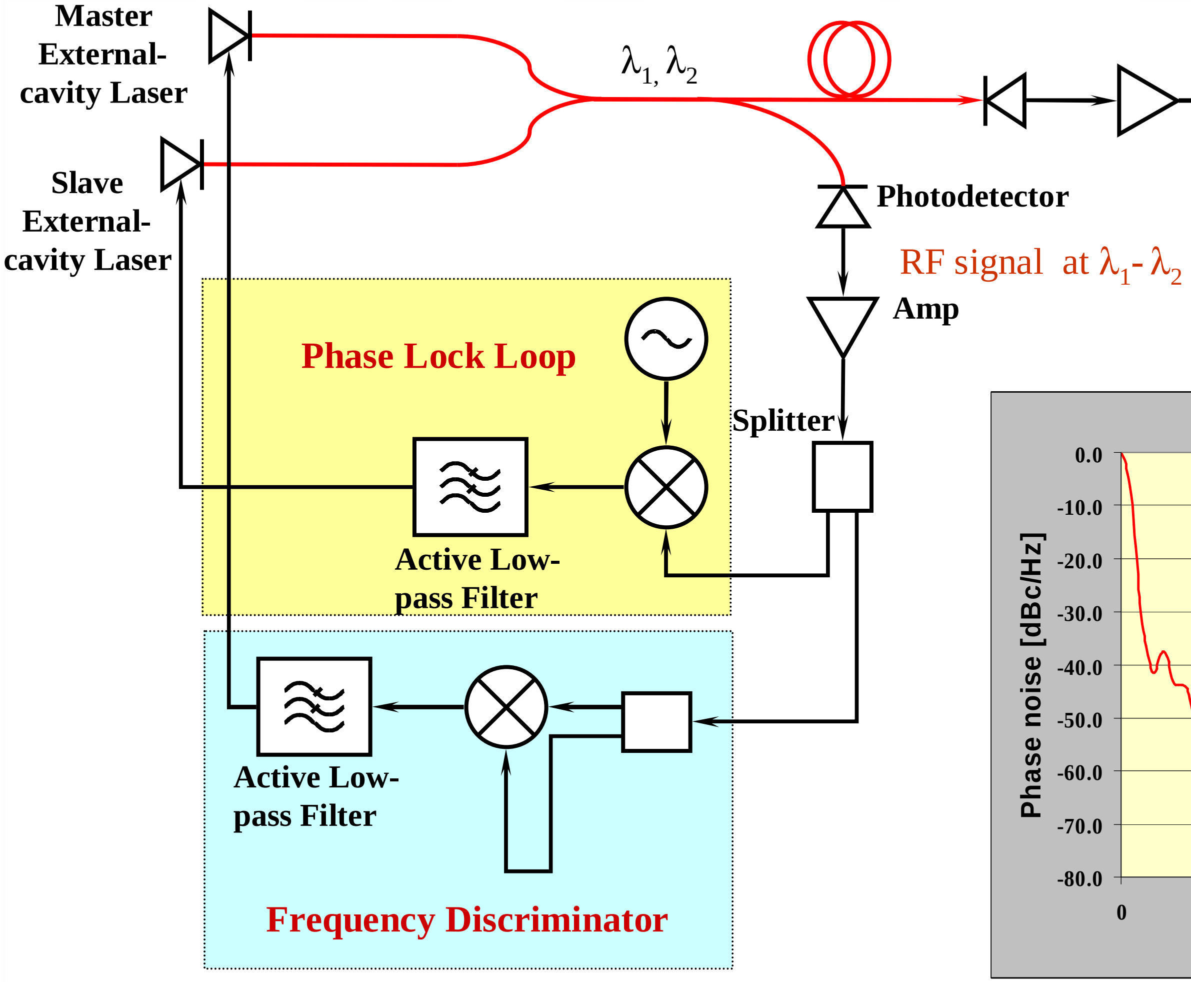





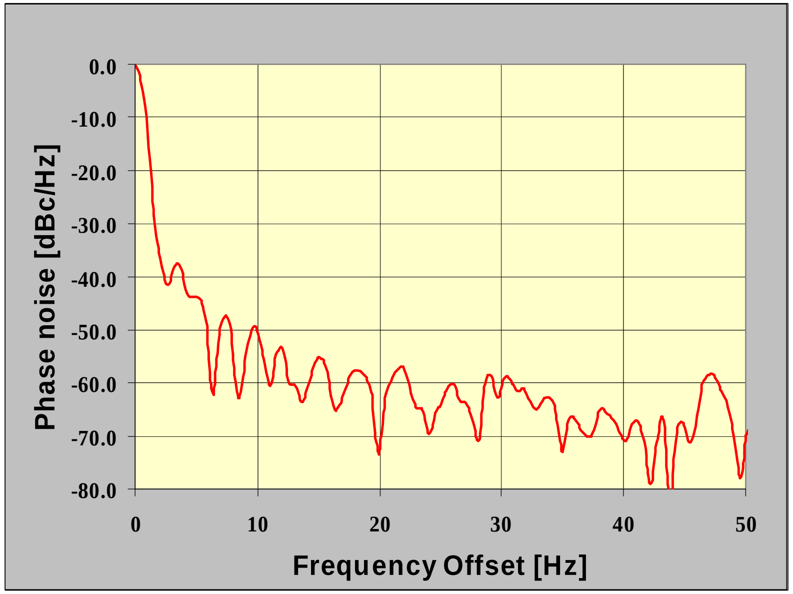

**Collaboration with:**

UNIVERSITÉ DE SHERBROOKE

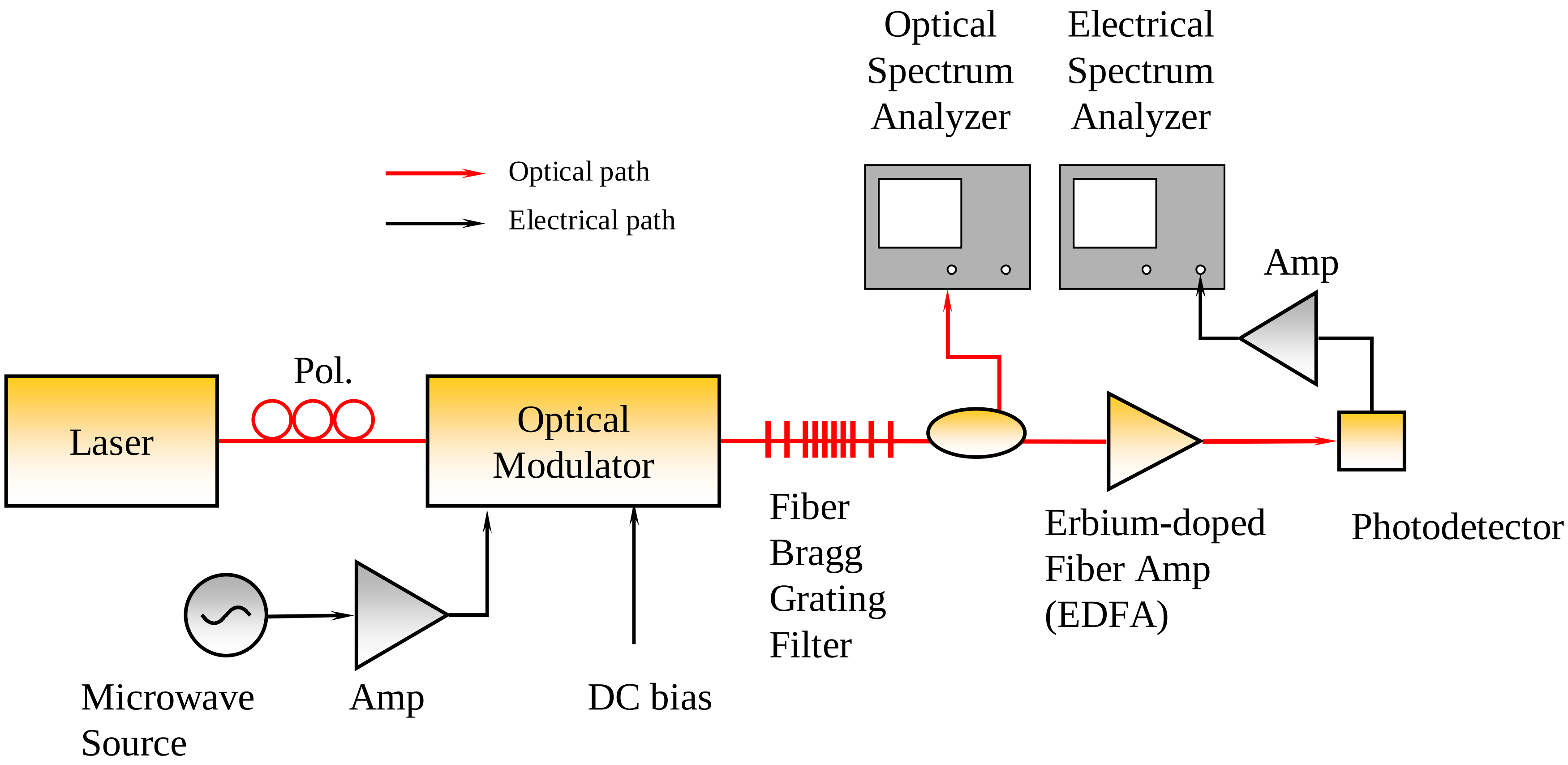
# Optical Phase-Locked Loop (PLL)



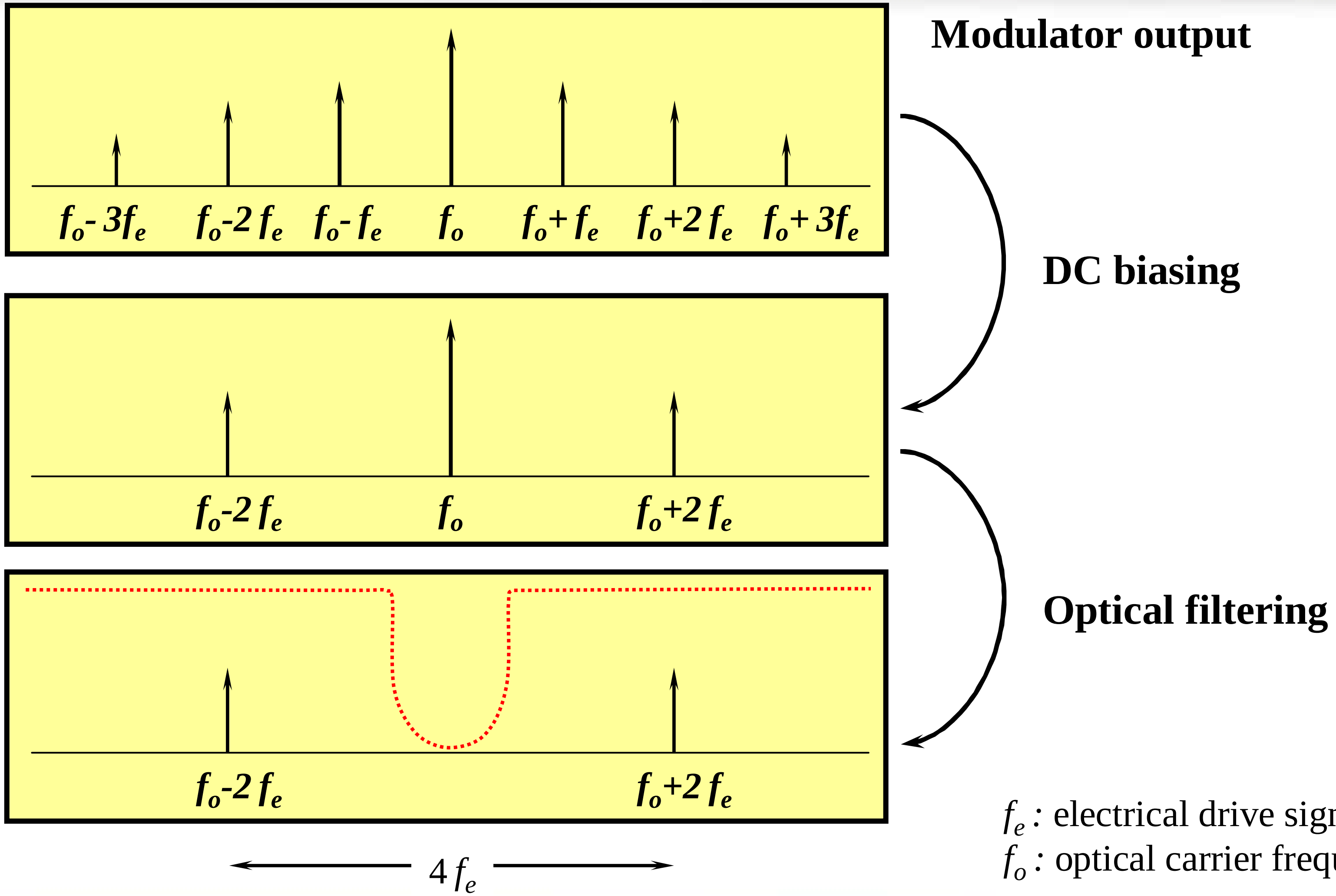

11.224 GHz operating frequency



# Single-laser Heterodyne Scheme



# Operating Principle



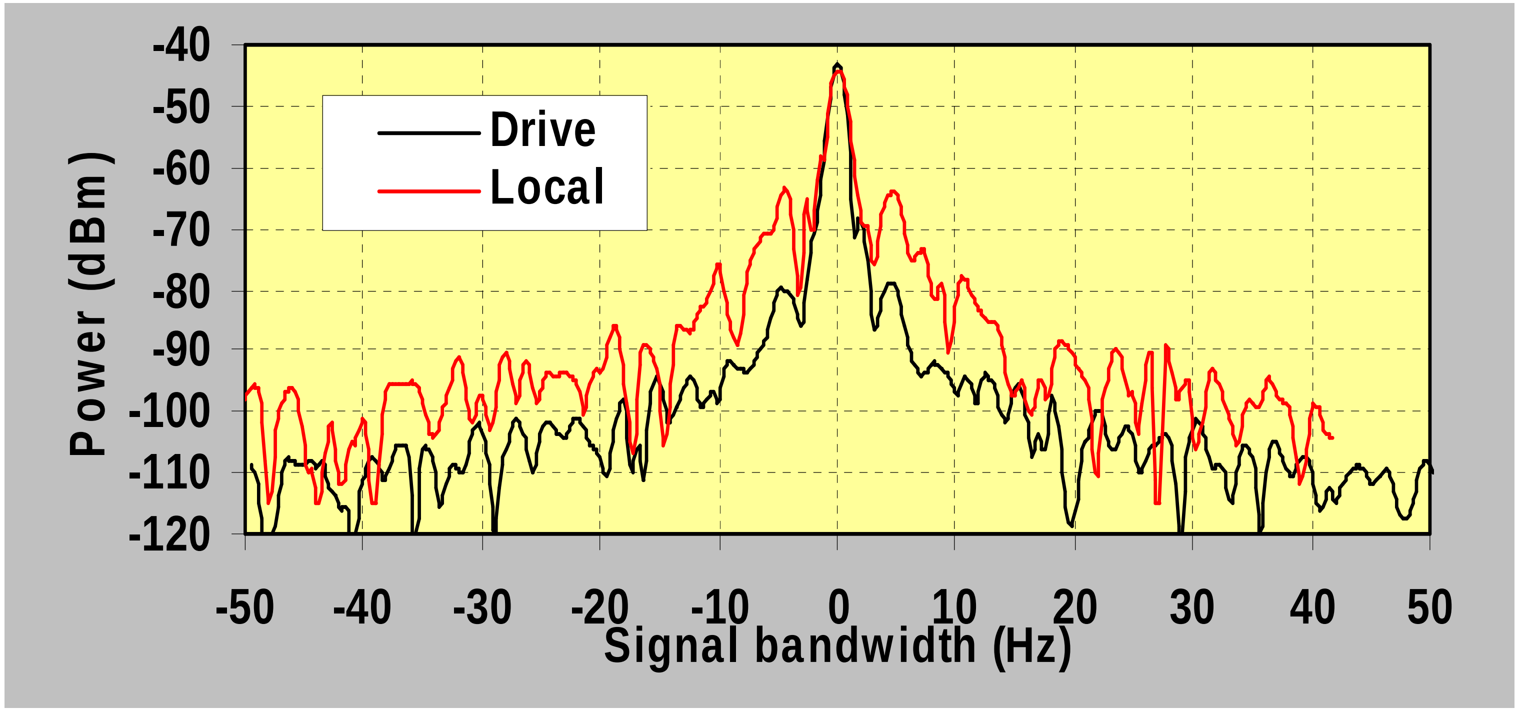

$f_e$ : electrical drive signal frequency

$f_o$ : optical carrier frequency

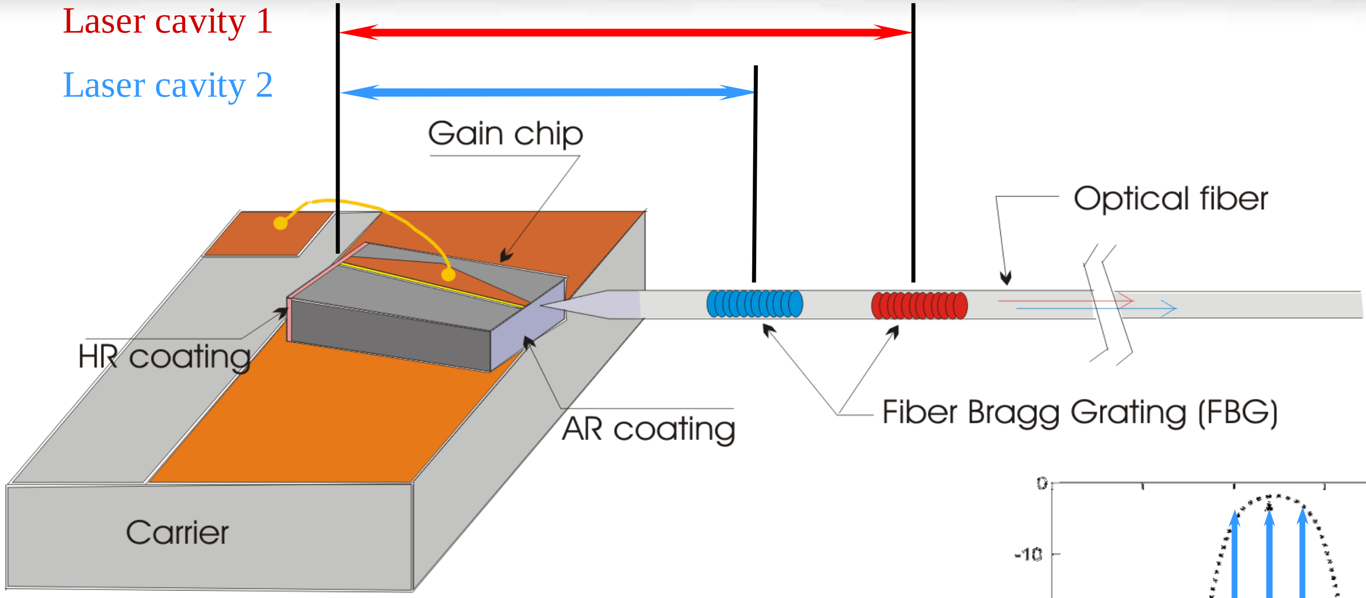
# Experimental Results

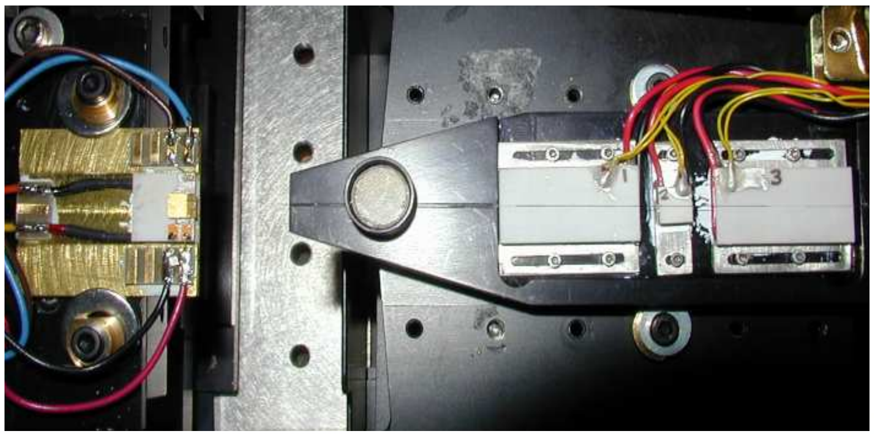
Drive signal: **12.5 GHz** (-48 dBc/Hz@10Hz)

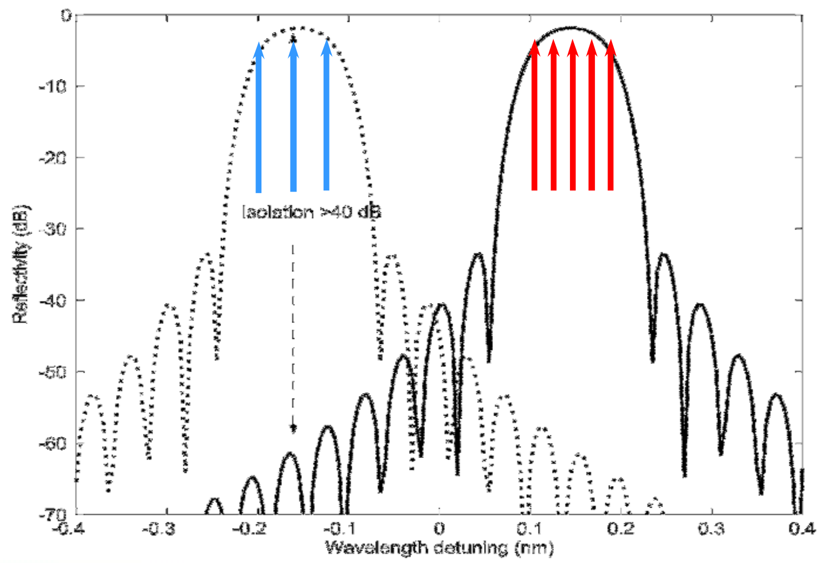
Local electrical signal: **50 GHz** (-35.5 dBc/Hz@10Hz)



# Dual-Frequency ECL



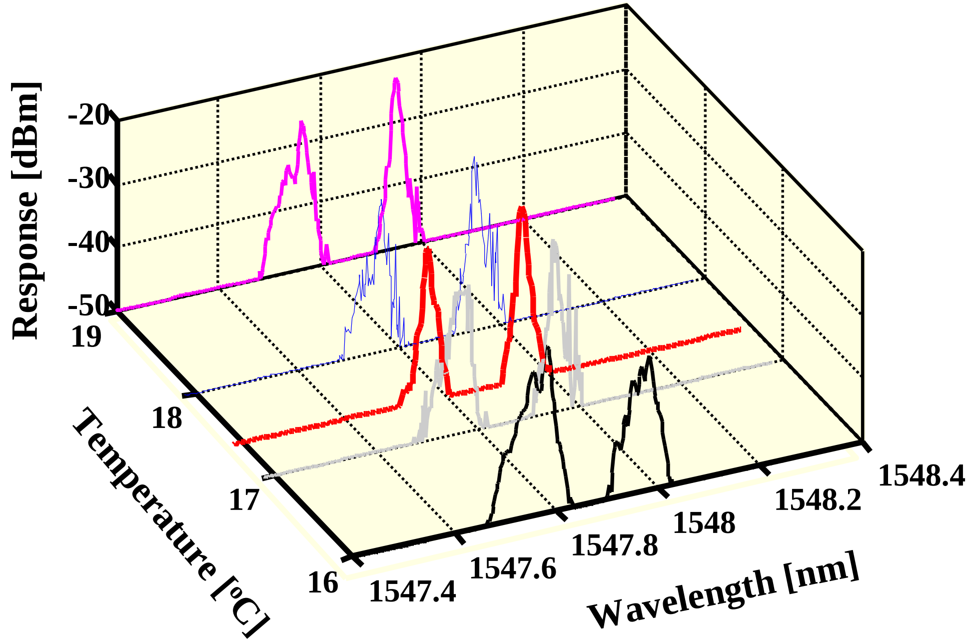





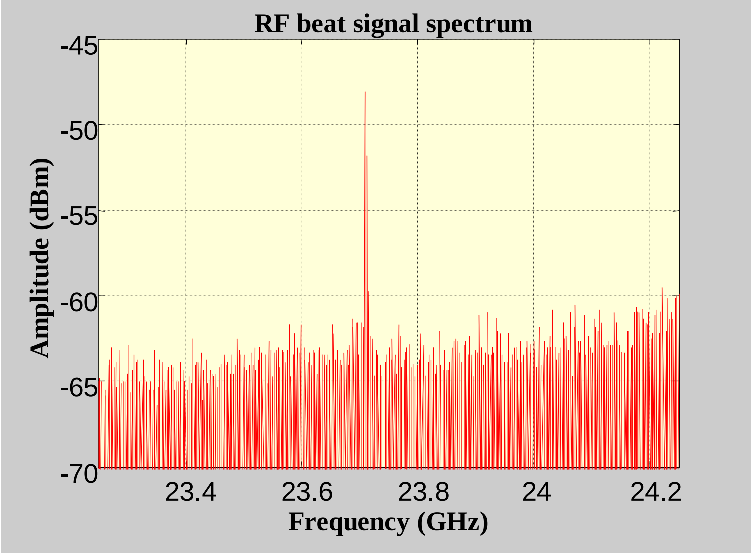
# Phase Control in Cavity

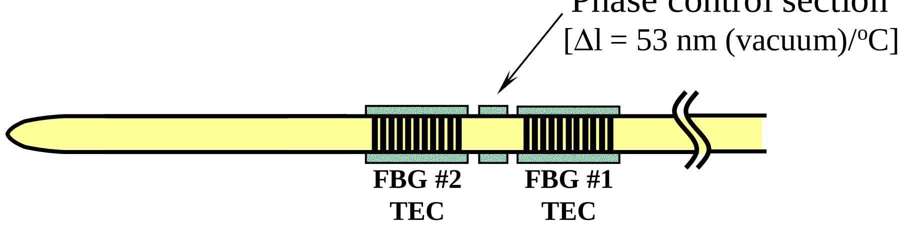


**Optical Domain**



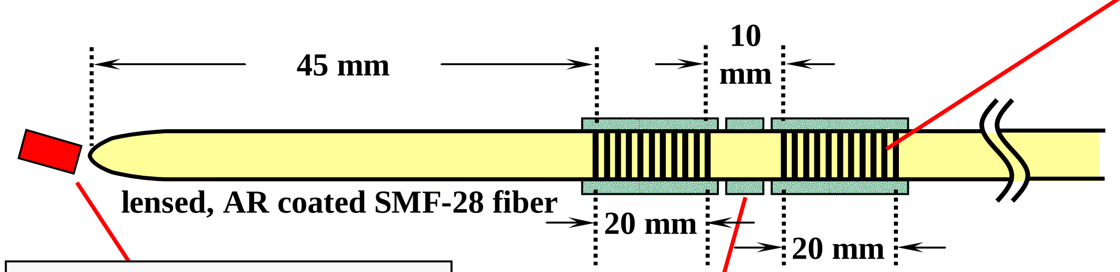

**Electrical Domain (for 17.4 °C)**



# External Cavity Laser Details

## Laser Diode configuration:

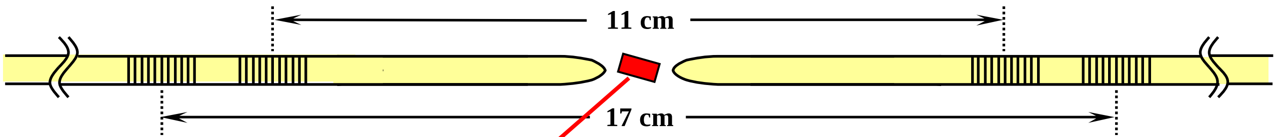



**APODIZED GRATINGS:**
- Peak reflectivity is 80%
- 3-dB bandwidth is 0.1 nm
- pitch L = 1.07 mm
- Bragg wavelength difference was around 0.25 nm

**GAIN CHIP:**
- Inphenix Model No. IPSGC 1550
- outer facet HR coated (95%)
- inner AR coated (0.01%)

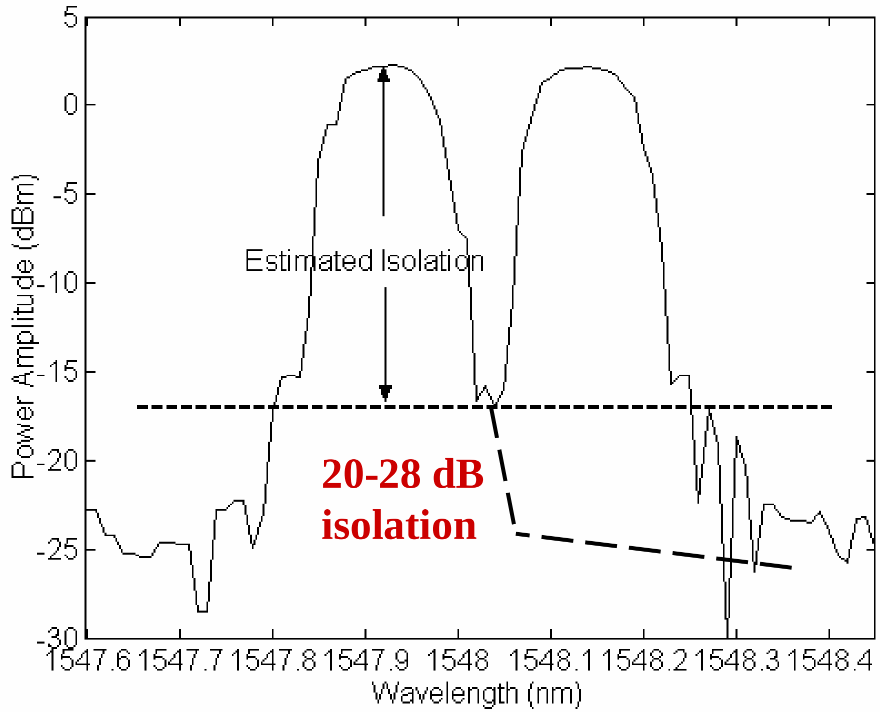
**TEC:**
- TEC under each FBG.
- 6-mm-wide TEC under the bare fiber section to act as a feedback phase controller

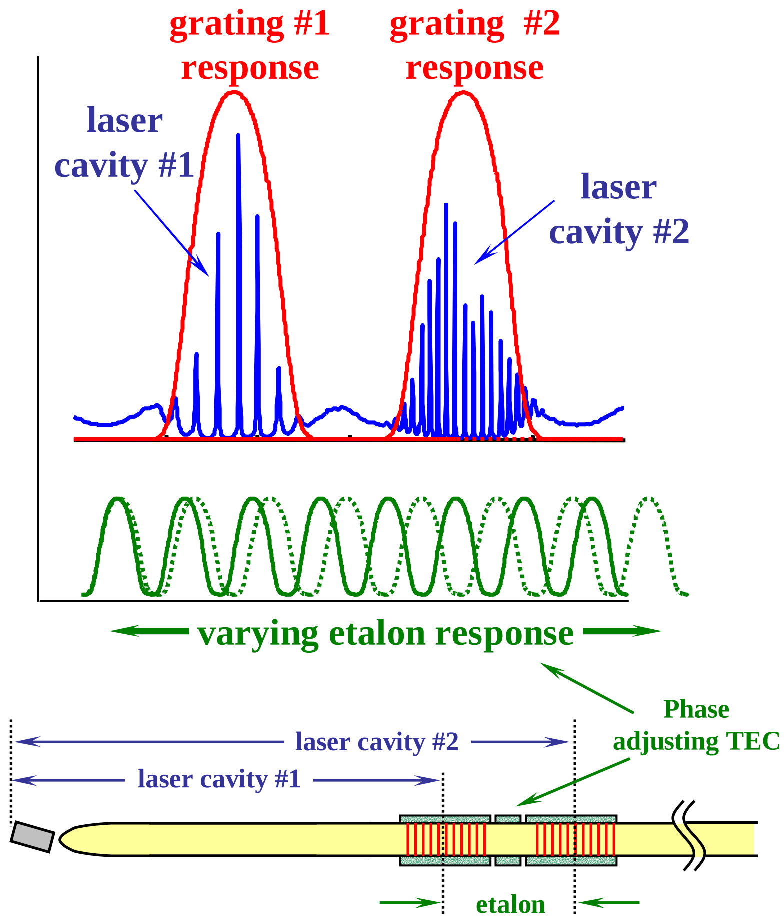
## SOA configuration:




**SOA:**
- Inphenix Model No. IPSAC-1503.
- Similar to laser diode with both facets AR coated.

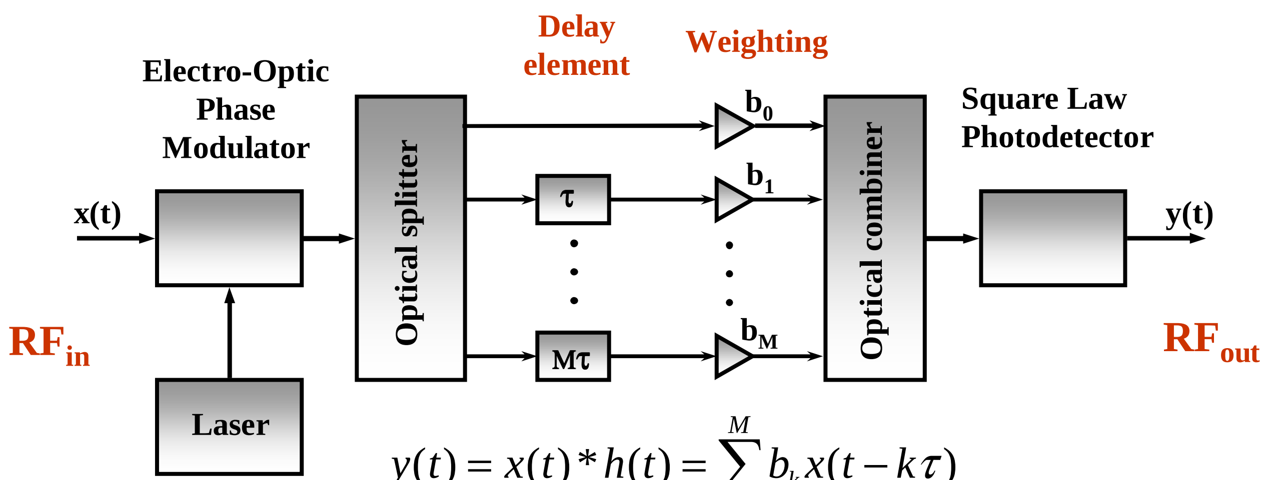
# Grating Performance and Multiple Reflections in Cavity



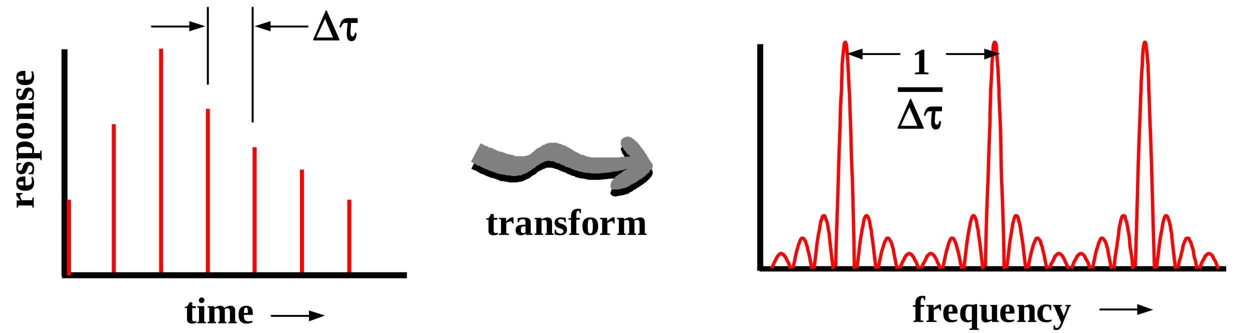



# Optical RF Filter Response

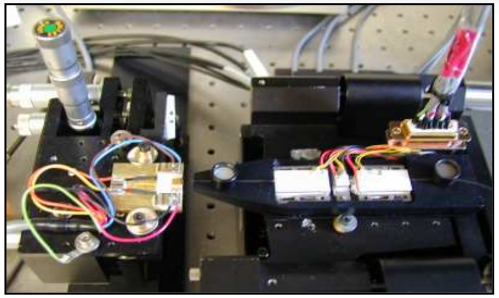
## Tapped delay-line device (FIR)

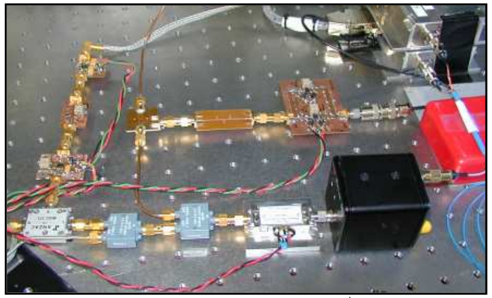


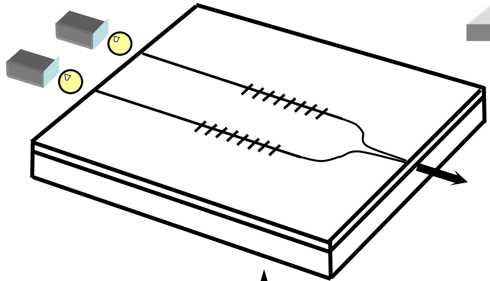

$$y(t) = x(t) * h(t) = \sum_{k=0}^{M} b_k x(t - k\tau)$$

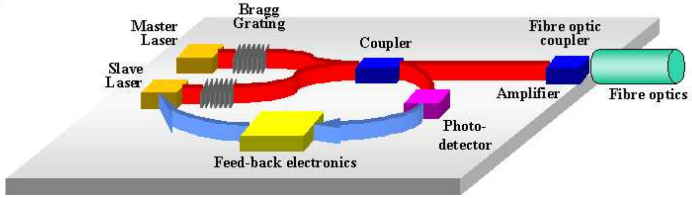


# Photonic Integration










Discrete Components

Partially Integrated in Silica

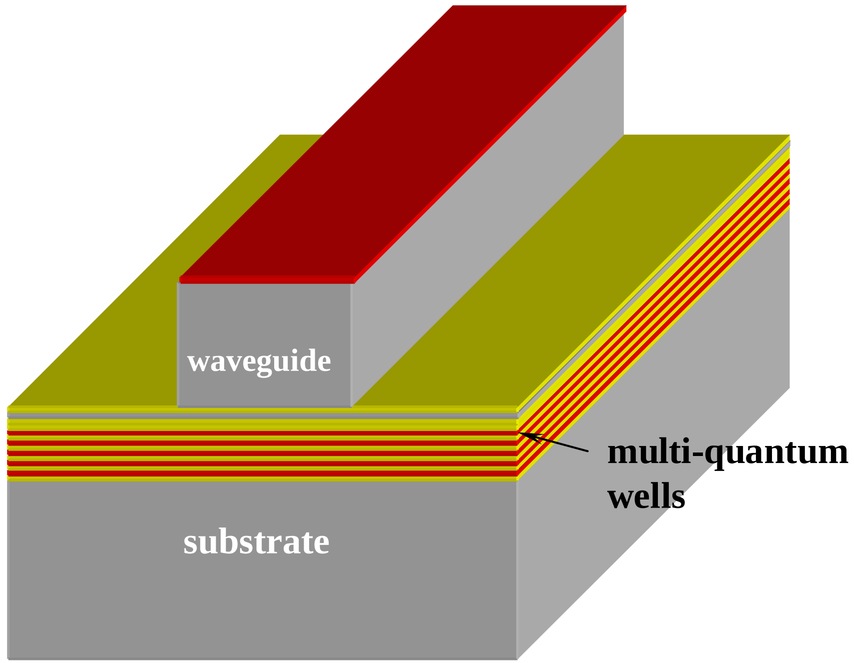
Fully Integrated in MQW InGaAsP

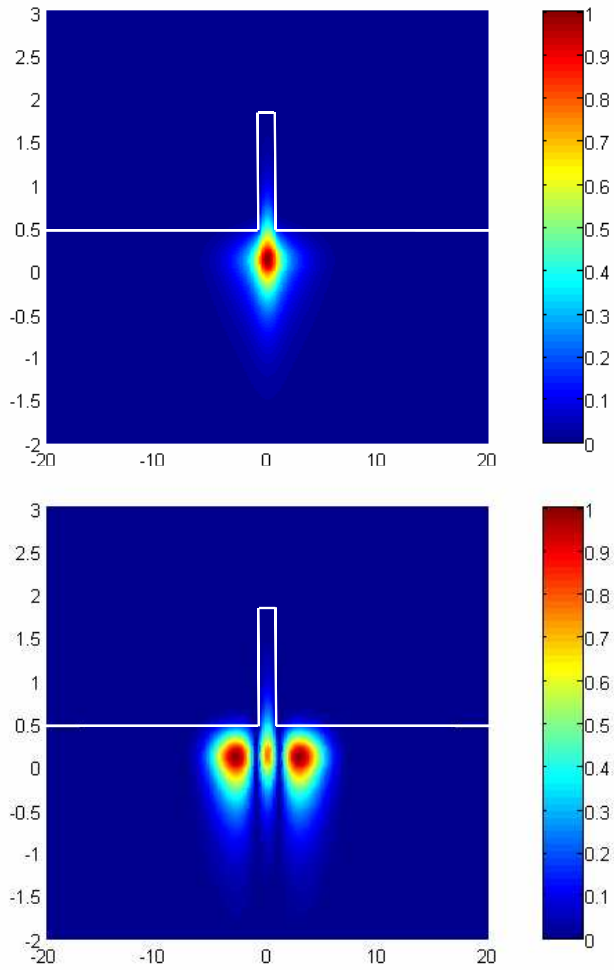
**Short Term** → **Long Term**

**A collaboration with**

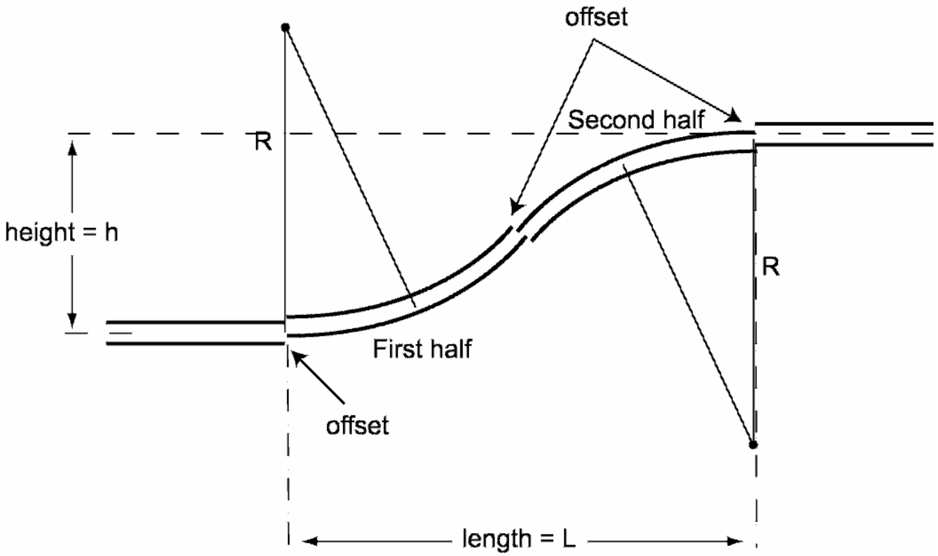
Photonics Wireless, uOttawa, Université de Sherbrooke, Dalhousie University, CRC

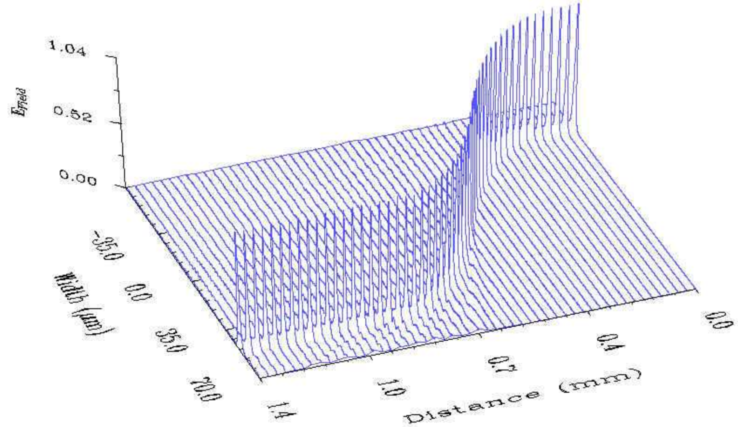
# Modal Distribution in Linear Waveguides

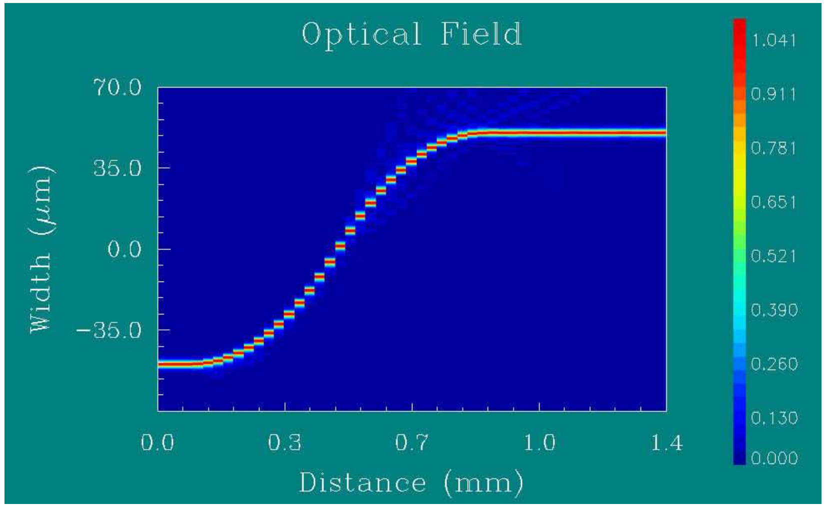


# Circular Bend Characteristics

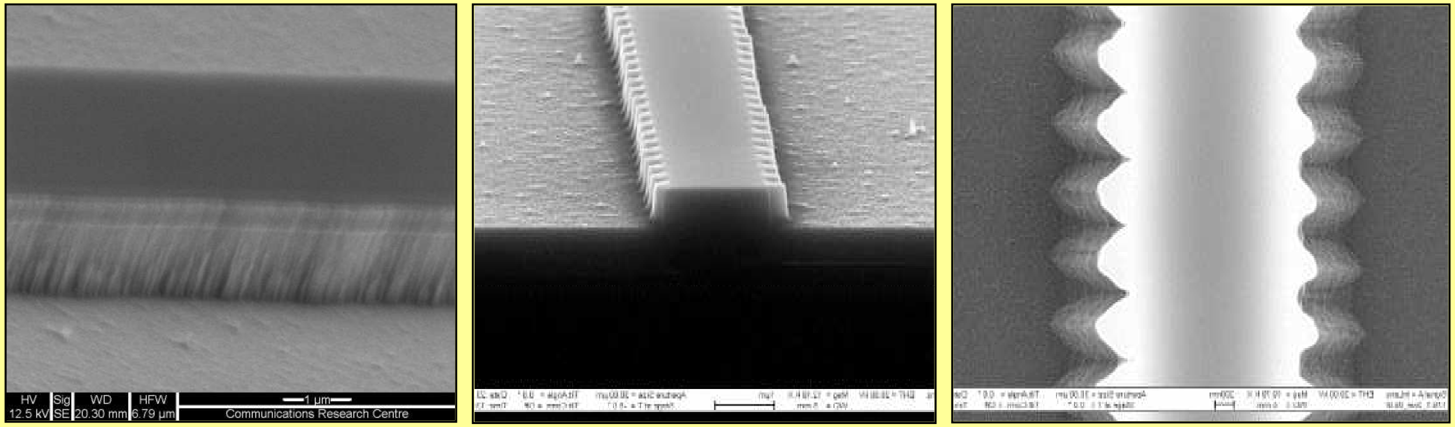


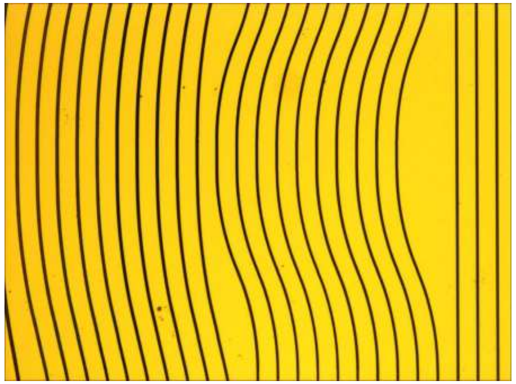



# Fabrication of PIC Elements






**first-order grating etched in a waveguide**



**multiple waveguides on substrate**

**Mode-locked Laser**

**Collaboration with**
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# Summary

- **Flexible RF hardware is a key feature to enable full potential of SDR,**

- **Optical technology can provide a continuously tunable modulated carrier up to 50 GHz using COTS components and can potentially work to beyond 1000 GHz,**

- **Proof-of-concept has been performed in the lab,**

- **Work has been initiated on the fabrication of a photonic integrated circuit for high volume production.**

# CRC = Innovation

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