Wavelength-to-time shape generation in the RF domain based on dispersion of incoherent optical carriers

Damià Torres Latorre and Alejandro Martínez Sánchez
Universitat Politècnica de Catalunya
(Dated: June 5, 2018)

This article proposes an experiment to check how dispersive fibers work. An electrical pulse is modulated by using an optical carrier which passes trough a medium with high dispersion coefficient, the same case that [1]. This article then proposes a technique to modify the shape of the original pulses whose experimental verfication has been seen beyond the capabilities of the current laboratory devices. Some examples of these applications can be seen in [1] and in [2].

Keywords: Dispersive media, waveform generation, real-time Fourier transform.

I. INTRODUCTION

Advances in the field of photonics have allowed the use of new techniques such as modulating an electrical signal through an optical carrier. This creates new ways of research since the optical carriers can have different behaviors depending on the medium they traverse.
The fact of undergoing non-uniform modifications, in this case depending on the wavelength, can have advantages as long as the behavior of the optical carrier is known exactly. This article explains the behavior of electric pulses modulated by optical carriers when traversing dispersive media. An application of this technique is proposed to modify the shape of the pulses, allowing to calculate ultrafast real-time Fourier transforms and to generate waveforms with amplitude variations in the RF time scale.

II. EXPERIMENTAL SETUP

The setup for our experiment can be seen in Figure 1, the main source is an Erbium Doped Fiber Amplifier (EDFA) which has no input. The main source of noise for the EDFA is amplified spontaneous emission (ASE) in this case we are using this noise as a source of power. With this use the EDFA provides a broad band from 1530nm to 1560nm, with a maximum in 1535.68nm. The output of the first EDFA goes to the waveshaper, which is a device that can modify the amplitude (only by attenuation, the waveshaper does not amplify) and the phase of every different value of λ. In this experiment the waveshaper was the model "WaveShaper 1000S" frabicated by Finisar and this waveshaper was used as a band-pass filter with multiple number of bands. In this device is also possible to code a specific filter.
The output of the Whavesaper goes to the Mach-Zehnder Modulator (MZM). The Mach-Zehnder also receives an electrical pulse from the pulse generator and it modulates this pulse using the optical wave as optical carrier. This Mach-Zehnder is connected to a source which gives $3.2V$, this point is near the zero of the transfer function and at this voltage was the maximum power transmited.
The pulse generator is a system of tree devices, the main pulse generator which creates pulses of 10ns of duration, a compressor which transform this pulses into pulses of 150ps, and the function generator which creates a square wave that triggers the pulse generator. In this setup the output of the modulator has too low optical power (between -30dBm and -20dmB) so, in order to increase the power level we set a second EDFA which amplifies up to approximately 5dBm are reached. The output of this EDFA passes trough a dispersive fiber which applies a different delay at every different value of λ, this fiber also reduces the power level but with the second EDFA there was enough power for our purpose.

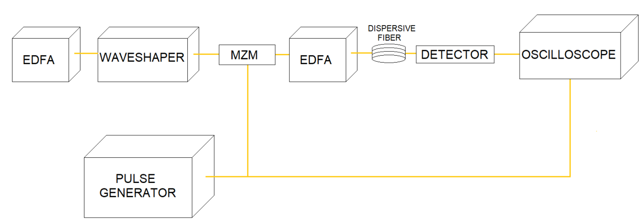

Figure 1. Schematic setup, showing the most important elements

We have used two different fibers one with a delay of -40ps/nm, and the other with delay -671ps/nm. Then the signal goes to a detector which transforms into an electrical signal and goes to the oscilloscope. The oscilloscope was the last device of this setup, it has also the output of the pulse generator in other channel in order to compare both signals. The oscilloscope resolution was 10GHz which is 100ps. The specifications of the pulse compressor are pulses of 35ps of duration but when we connected this to the oscilloscope we saw pulses of approximately 150ps but this pulses were short enough for our purpose.

III. THEORETICAL BACKGROUND

To study the propagation of an optical signal trough a dispersive medium, we recall the slowly varying envelope approximation, i. e., as the frequency of the oscillation is much higher than the scale of the variation of amplitude, it's appropiate to write the scalar field (in a one-dimensional model of a monochromatic wave) as:

$$E(t) = E_0(t)e^{-iw_0 t}$$

In our experiment, the optical source of power has a wide band, hence, by the superposition principle we can describe the optical input (before filtering and modulating), setting w_1, w_2 the minimum and maximum frequencies:

$$E(t) = \int_{w_1}^{w_2} E_0(w,t)e^{-iwt}\mathrm{d}w$$

As the EDFA is an incoherent random source with a nearly constant spectral power output, we will asume $E_0(w,t) = E_0(w)$ is constant in time. After the generation, a wavelength-dependent filter is placed, which corresponds to multiplying each carrier amplitude by some factor, $F(w)$. Afterwards, the signal transverses a MZM acting as an envelope shaper, which introduces an actual time dependence, converting the signal to a recurrent pulse. Putting all together, if we call $P(t)$ the temporal power distribution given by the modulator (affecting all the frequencies in the same way), the wave entering the dispersive element can be written as:

$$E(t) = P(t)\int_{w_1}^{w_2} E_0(w)F(w)e^{-iwt}\mathrm{d}w$$

And letting the beam pass through a dispersive medium, a different time delay occurs for each frequency, and we can write this effect by introducing the travel time, $T(w)$ through a distance at different speeds.

$$E(t) = \int_{w_1}^{w_2} P(t-T(w))E_0(w)F(w)e^{-iw(t-T(w))}\mathrm{d}w$$

As the dispersion of fibers is usually known as a function of the wavelength, it is convenient to use the relation $\lambda = 2\pi c/w$ to write:

$$E(t) = \int_{\lambda_1}^{\lambda_2} P(t-T(\lambda))E_0(\lambda)F(\lambda)e^{-(2\pi ic/\lambda)(t-T(\lambda))}\mathrm{d}\lambda$$

And taking λ_0 a central carrier, D the dispersivity , we have also $T(\lambda) = T(\lambda_0) + D(\lambda - \lambda_0)$. It's also convenient to recall that the measure system has a response time much larger than the scale of the oscillations of the wave, so we are averaging the term $e^{-(2\pi ic/\lambda)(t-T(\lambda))}$ and we can, in fact, ignore it. Finally, if the pulses in the modulator are short enough, $P(t-T(\lambda)) = \delta(t-T(\lambda))$. With all the approximations, and calling $I = E_0 F$ we attain the expression in [1]:

$$E(t) = \int_{\lambda_1}^{\lambda_2} \delta(t - T(\lambda_0) - D(\lambda-\lambda_0))I(\lambda)\mathrm{d}\lambda =$$

$$= I(\lambda_0 + \frac{t-T(\lambda_0)}{D})$$

This is the principle of wavelength-to-time mapping, the spectral distribution of power becomes also a temporal distribution of power after the different delays in each spectral component induced by the dispersive medium. It is readily seen that $E(t+T(\lambda_0)) = I(\lambda_0 + t/D)$, and to generate a specific output temporal shape what we need is to have the same shape in the spectral domain after filtering. As the power source has a nonconstant spectral power density, the filter needs to take it into account, yielding to the filter design equation:

$$F(\lambda_0 + \Delta\lambda) = \frac{E(T(\lambda_0) + D\Delta\lambda)}{E_0(\lambda_0 + \Delta\lambda)}$$

A. Real-time Fourier transform

Recalling the equation that maps the spectral power density before the dispersive medium and the output temporal power distribution, it is readily seen that both signals have the same shape up to a change of scale, this is, the output function is the (averaged, as oscillations as fast as those of the optical carrier aren't taken into account) Fourier transform of the input signal, this is, the spectrum of it. This reminds us of the effect of the diffraction, where at long distances the pattern observed has the shape of the Fourier transform of the shape that produces the diffraction [3]. See Figure 2.

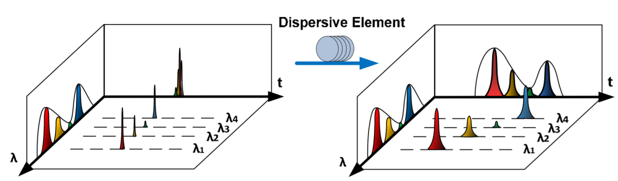

Figure 2. Sketch on how dispersion maps the spectral distribution of power to a temporal one [4].

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The first dispersive element has a value of $DL = -671$ps/nm, and the pulse generator has an alias about 12ns, as can be seen in Figure 3 after the main pulses, so we need to work with pulses that are still shorter than this time after dispersion, which yields about 17nm of usable bandwidth from the EDFA without aliasing the output signal. The second one has a value of $DL = -40\text{ps/nm}$, which, as is far shorter, makes no problem with aliasing, but it can only shape much shorter pulses (up to 1ns, as the limited bandwidth of the EDFA becomes relevant).

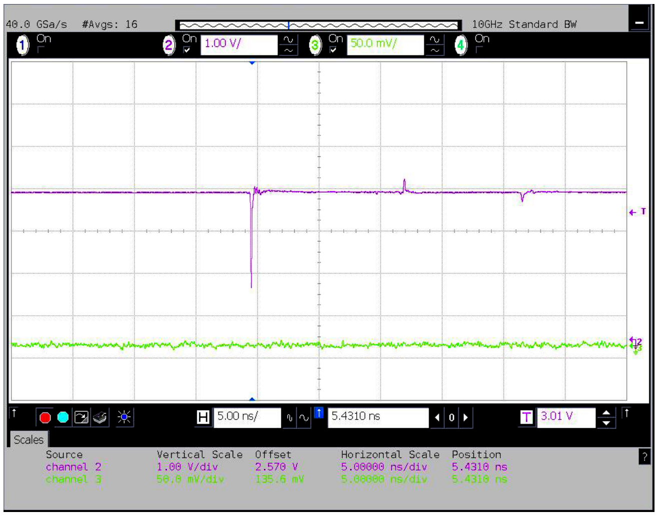

Figure 3. Screenshot of the oscilloscope that shows the pulse created by our pulse generator that shows the alias (green colour).

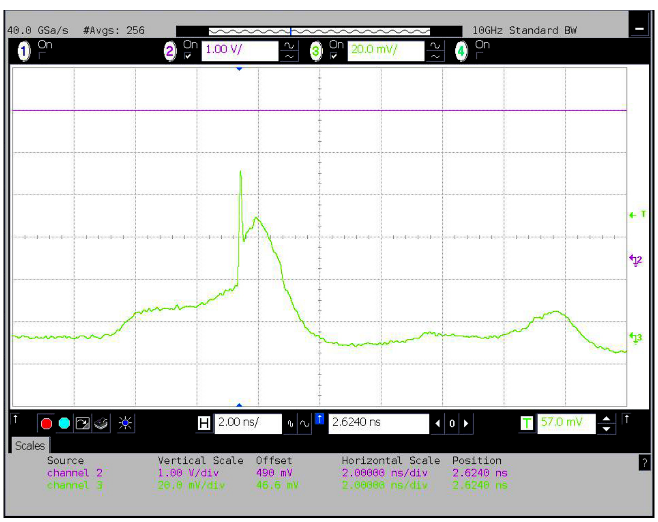

Figure 4. Screenshot of the oscilloscope that shows the spectrum which is inverted.

A. Initial working setup

In order to capture the *zero point* of the experiment, this is, the EDFA spectrum affected by all the connectors and measure devices, a band-pass filter $(1533 - 1543\text{nm})$ is set with the first dispersive element, and from it $E_0(w)$ is readily obtained. The 10nm of original band become about 7ns, as expected. Notice also that the spectrum is inverted, because $D < 0$ as can be seen in Figure 4.

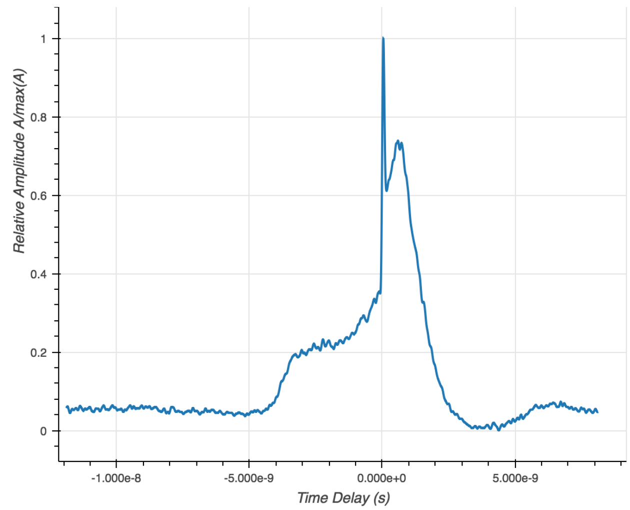

Figure 5. Plot of the output zero point function, $E_0(t)$, centered at the time of arrival of the $\lambda_0 = 1535\text{nm}$ component.

B. Band-pass filtering and aliasing

In the experiment it is also shown what happens when the pulse is not approximable by a delta function. In this cases, the temporal output shape is the convolution of the dilated spectral figure with the original shape of the pulse. This effect is checked when we capture $E_0(w)$, but also with a two-band-pass filter (bands at $1536, 1540\text{nm}$, 1.5nm bandwidth).

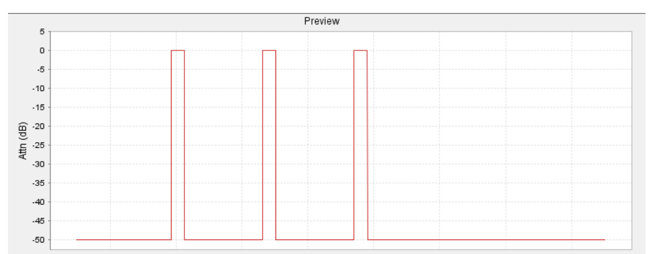

Figure 6. Screen of the waveshaper with the tree-band-pass filter. The tree bands are centered in 1535, 1542 and 1549nm and have 1nm of bandwidth

The effect of wavelength-to-time mapping is checked also using a three-band-pass filter (bands at $1535, 1542, 1549\text{nm}$ of 1nm bandwidth see Figure 6), by means of the second dispersive fiber. The result was Figure 7, one encounters a severe variation in the output power even in this close range, which is a major difficulty to make arbitrary shapes in this fashion, due to a significant loss of total power (the shape is limited in amplitude by the least favorable of all the wavelengths it must contain). This particular measure is also useful to check the validity of the model on the dispersion, as 7nm of difference in wavelength become about 280ps, and again the spectrum is reversed.

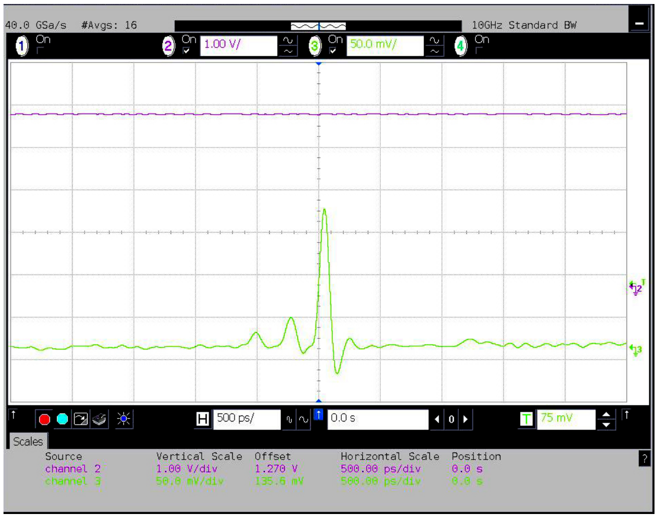

Figure 7. Result after passing trough the dispersive fiber of -40ps/nm which shows 3 peaks, the biggest one corresponding to the maximum of the EDFA (1535nm) is the last in this picture because the spectrum is reversed.

C. Arbitrary form generation

A software to calculate the attenuation for each frequency the waveshaper should use, $F(w)$, was implemented. Using the filter design equation, a filter to obtain a triangular pulse was calculated. Using Figure 8 as a reference, we see that a severe cut in power needs to be done around the maximum power of the EDFA sources (aronud 194.05THz), and that, in order to obtain the desired shape, the total power output is drastically reduced. The main limiting factor is the use of a broadband source, and in order to complete arbitrary form generation an ultrashort laser pulse source would be required.

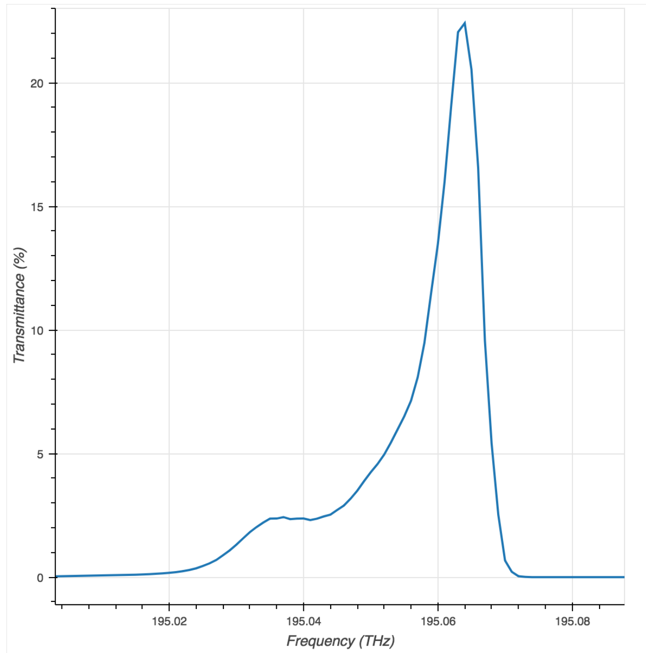

Figure 8. Plot of $F(w)$ to obtain a triangular pulse.

V. CONCLUSIONS

We designed a setup to generate arbitrary waveforms in the optical domain at a RF time scale using an incoherent technique and demonstrated the fundamentals of its operation. The scheme uses a wide band source (EDFA), a spectral domain waveshaper, a Mach-Zehnder Modulator and a DCF link. We obtained some different shapes and checked that, as the waveshaper is completely freely configurable in the wavelength domain, these could be changed arbitrarily, and implemented a way to compute the required filters to generate them.

---

[1] ”Photonic generation of arbitrary waveforms based on incoherent wavelength-to-time mapping”. Dong Jian-Ji , Luo Bo-Wen, Yu Yuan, and Zhang Xin-Liang. Chin. Phys. B Vol. 21, No. 6 (2012)

[2] ”Photonic generation of W-band arbitrary waveforms with high time-bandwidth products enabling 3.9 mm range resolution”. Yihan Li, Amir Rashidinejad, Jhih Min Wun, Daniel E. Leaird, Jin-Wei Shi, and Andrew M. Weiner. Optica / Vol. 1, No. 6 / December 2014

[3] ”Dispersive Fourier Transformation for Versatile Microwave Photonics Applications”. Chao Wang. Photonics 2014, I.

[4] ”Photonic synthesis of high fidelity microwave arbitrary waveforms using near field frequency to time mapping”. Amir Dezfooliyan1 and Andrew M. Weiner. OPTICS EXPRESS, 23 September 2013 — Vol. 21.