Generation of a reference frequency comb by cascaded four-wave mixing enhanced by Raman amplification

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Abstract

The generation of standard reference frequencies close to the ITU channels is essential for the calibration and maintenance of DWDM systems. This paper describes the generation of a reference frequency comb based on cascaded four-wave mixing in two semiconductor optical amplifiers enhanced by Raman amplification in a dispersion-shifted optical fiber. As a result we have achieved a stable frequency comb with 36 reference lines separated by a constant frequency spacing of 177 GHz. The seed of the comb is combination of two narrow-linewidth semiconductor lasers which are locked to two absorption lines of the acetylene ($^{12}C_2H_2$).

Key words: Standard frequencies, four-wave mixing, semiconductor optical amplifier, Raman amplification, frequency comb.

1. Introduction

In Dense Wavelength Division Multiplexing (DWDM) systems, the data is transmitted over a single mode optical fiber using multiple optical frequency channels following a frequency grid centered at 193.1 THz (1552.525 nm) in which the channels are separated by 100, 50 or 25 GHz. With such a narrow spacing, accurate frequency stabilization of the optical carrier frequencies is required to ensure robust transmission and avoid possible crosstalk between adjacent channels and losses in the filtering systems. For this reason, new frequency standards are necessary to calibrate the lasers, the filters, wavelength meters and optical spectrum analyzers used in the maintenance and characterization of DWDM systems.

An interesting method to generate reference frequencies in the optical fiber communications bands is the stabilization of lasers in the molecular or atomic absorption lines of some specific gases. The absorption lines of gases such as acetylene, hydrogen cyanide, methane, carbon dioxide, carbon monoxide and hydrogen fluoride, working with their different isotopes, provide frequency references that are very stable under changing environmental conditions and have a well-known response in the spectral bands used in optical fiber telecommunication, from about 184 THz to 237 THz (1625-1260 nm) [1, 2, 3, 4, 5].

The main problem with the generation of reference frequencies based on the absorption lines of gases is the fact that the obtained frequencies appear in spectral regions in which the gas used presents well-resolved absorption lines. If we want to obtain reference lines covering most of the telecommunications spectrum, it is necessary to use more than one cell. This approach is expensive since it requires several reference cells with accurate traceability. A couple of solutions to this problem have been demonstrated, by generating frequency references based on standard absorption lines using four-wave mixing in optical fiber [6] and in semiconductor optical amplifier [7].

Another important and useful method in the fields of optical metrology and spectroscopy is the generation of a frequency comb. The comb enables difference frequency measurement and frequency calibration over a broad bandwidth of actuation. For this reason, a frequency comb generation is an important method to generate the wide number of optical channels required by DWDM systems. We can find several examples in the literature on the generation of frequency combs by four-wave mixing

(FWM) controlled by the fiber dispersion [8], by the buildup of supercontinuum from a modulated source [9], and by the use of sampled fiber Braggs gratings [10, 11], by FWM in multicore photonic crystal fibers [12] or using a semiconductor optical amplifier and a Fabry-Perot filter in a fiber ring [13].

In this paper we demonstrate experimentally a constant frequency-spacing reference frequency comb based on cascaded degenerate four-wave mixing in two semiconductor optical amplifiers (SOAs) followed by further FWM enhanced by Raman amplification in a dispersion-shifted optical fiber. The seed of the comb is generated by locking two lasers into different absorption lines of acetylene $^{12}C_2H_2$, P23 (f = 194.743 THz, λ = 1539.46 nm) and P25 (f = 194.566 THz, λ = 1540.83 nm), centered close to the zero dispersion wavelength of the optical fiber used in the experiment. Through cascaded FWM, these two lines generate the rest of the lines of the frequency comb. Thus, the frequency difference between the selected absorption lines sets the spacing of the frequency comb (Δf=176.636 GHz, Δλ = 1.4 nm). To ensure a good FWM efficiency in the first steps of the comb generation we use two SOAs as a nonlinear medium. Furthermore in SOAs the phase matching condition is less restrictive than in fiber, which means that there is a wider bandwidth over which the conversion efficiency is significant [13, 14]. We use an external fiber and Raman amplification to broaden the comb, leading to the generation of up to 36 reference lines.

2. Experimental setup and results

Figure 1 shows the experimental setup for the proposed frequency comb that operates stably at room temperature.

The design consists of two tuneable lasers with a line width of 150 KHz, two cascaded SOAs with a saturation power of 13 and 15 dBm respectively, an isolator, two Raman fiber lasers at wavelengths of 1455nm and 1427 nm, a 5 Km dispersion-shifted fiber, an acetylene absorption cell manufactured and calibrated by NIST (SMR 2517a [15]), two optical filters and two lock-in amplifiers. The setup works as follows: the output of the tunable lasers is divided in two branches. One is used for stabilization of the two initial frequencies at the selected frequencies by means of the acetylene cell, and the other are coupled together and used for the frequency comb generation. To lock both lasers (TL1 and TL2) to the absorption lines of the acetylene cell used in our setup, we use a small frequency modulation, as in [7]. The peak to peak modulation of the laser frequency is 30 MHz. After passing through the acetylene cell, the signals emitted by both lasers are detected by two detectors and two lock-in amplifiers. These generate the error signal that is used to compensate the possible drifts in the frequencies of TL1 and TL2 from the absorption lines used (P23 and P25). In order to avoid possible interferences between the signals detected by the lock-in amplifiers, the laser beams were introduced in the absorption cell in opposite directions through two isolators, as shown in Figure 1 [7].

The two waves are polarization-controlled to maximize FWM efficiency. The SOAs are the first elements used for FWM generation. These SOAs are longer than conventional ones used for amplification, and hence exhibit a larger nonlinear behaviour. The two SOAs are cascaded in order of increasing output saturation power, so as to enhance the nonlinearities. Figure 2 shows the spectra obtained at the output of the first and second SOA, showing a consistent increase in the number of FWM products generated. It is possible to see that in the first SOA we obtained four new frequencies. After the second SOA the mixing product is enhanced generating seven new frequencies. The power of the lasers was $P_1 = 5$ mW and $P_2 = 6$ mW.

The output of the second SOA is introduced in a 5 Km long dispersion-shifted non-uniform fiber with a zero-dispersion wavelength of 1540 nm and a dispersion slope of 0.056 $ps \cdot nm^{-2} \cdot km^{-1}$. For the selected frequencies, the dispersion of this fiber seems suitable to improve the FWM generation and, due to its reduced effective area, the fiber also presents a relatively high Raman gain (3.3 $dB \cdot W^{-1} \cdot km^{-1}$). The benefits of introducing Raman gain in the fiber are double: first, since the power of the waves is increased, the efficiency of the FWM process (which depends on the cube of the power) is largely enhanced; second, the phase matching conditions of FWM are less restrictive, as it was shown in [6]. We enhance the efficiency of FWM generation in the fiber by means of a Raman pump tuned at 1455 nm.

Figure 3 shows the spectra obtained at the output of the fiber. For powers below 1 W, the number of visible lines increased with the Raman pump power. The optimum results with one Raman pump are obtained for a pump power of 1 W. In this case, the frequency comb generated consists of 28 equally spaced frequencies covering a range from 1522 nm to 1561 nm with reference in the in the absorption lines acetylene $^{12}C_2H_2$. As we were increasing the pump power, we could check that the number of frequencies generated did not increase. As Figure 3 shows, pump powers higher than 1 W increase the output power of the comb but diminish the OSNR of the frequencies generated by increasing the noise of the system.

Therefore, in order to increase the number of frequencies generated we introduced another Raman Fiber Laser, RFL_2 whose center wavelength is tuned at 1427 nm and with a maximum output power of P_{p2} = 2W. Both lasers were introduced through the same WDM by means of a 50/50 coupler. The purpose of this pump is to enhance the FWM efficiency for higher frequencies (shorter wavelengths). Figure 4 shows the optimum output spectra obtained with the double Raman amplification. The pump powers inserted in the coupler were 1 W for the RFL_1 and 2 W for the RFL_2. The new frequency comb generated consists of 36 equally spaced frequencies covering a range from 191.56 THz (1565 nm) to 197.88 THz (1515 nm) with reference in the in the absorption lines acetylene $^{12}C_2H_2$.

The main difficulty found in the generation of this frequency comb arrives from the competition between non-linear effects inside the dispersion-shifted fiber. The linewidth of the lines emitted by our lasers is very narrow (150 kHz bandwidth). This contributes to generate a strong backward stimulated Brillouin scattering signal. The Brillouin scattering subtracts energy of the comb lines, thus reducing the FWM generation. To overcome this limitation, it would be necessary a dithering of the initial wavelength emitted from the lasers. However, this would enlarge the line width of the lasers, hence introducing a larger uncertainty in the stabilization and the position of the comb lines.

From the well-known physics of FWM, it is known that the FWM efficiency is maximal when the wavelength of the pump lies the fiber zero-dispersion wavelength, i.e. when the phase matching condition is satisfied. Hence, as the frequencies involved in the FWM are detuned from the zero-dispersion frequency the chromatic dispersion of the fiber introduces a large phase mismatch between the waves that produces a decrease in the FWM efficiency [15].

3. Uncertainty estimation for the new frequencies generated.

The uncertainty of the frequencies generated depends on the uncertainty due to the absorption references (values given by NIST [16]) and the width of the laser emission lines stabilized in the absorption lines of the acetylene. The calculation of the uncertainty is different depending on whether it is the first generation (the generation is carried out with both lasers locked into the acetylene absorption references), or it is a secondary order FWM product. The difference between the two cases lies in the linewidth of the lasers that synthesize the new frequency. In the first case the linewidth is only broadened by the modulation (30 MHz), in the second case the linewidth is the result of the combination of the linewidth broadening due to the modulation and the additional broadening due to mixing. We have experimentally observed that in our system the average broadening of linewidth of the mixing increase approximately √2 the broadening of linewidth due to the modulation in every product.

Tables I, II and III show the uncertainties corresponding to the generation of three frequencies, 194.92 THz, 195.197 THz and 195.45 THz. The new frequency references generated in these examples have an uncertainty of 194.920175±0.000066, 195.097805±0.000122 and 195.453065±0.000204 respectively (k=2).

The uncertainty related to the stabilization of the lasers in the acetylene absorption lines was evaluated by statistical analysis of a series of observations (uncertainty type A). The other uncertainties involved in the process were evaluated from the specifications of the devices and data provided in calibration certificates (uncertainty type B).

4. Conclusions

In summary, we have experimentally demonstrated a constant spacing frequency comb based on cascaded four-wave mixing in two semiconductor optical amplifiers (SOAs) enhanced by Raman in a dispersion-shifted fiber. The seed of the comb are two frequencies that are stabilized in two absorption lines of the acetylene. The spacing of the frequency comb is set by the frequency difference between the two absorption lines used. The frequency comb generated consists of 36 equally spaced frequencies (176.636 GHz, 1.4 nm) covering a range from 191.56 THz (1565 nm) to 197.88 THz (1515 nm). This frequency comb could be useful for wavelength metrology to calibrate DWDM systems such as wavelength meters or optical spectrum analyzers, for the generation of precise multiwavelength sources employed in DWDM and for synchronization of different fiber laser-based frequency combs.

5. Acknowledgements

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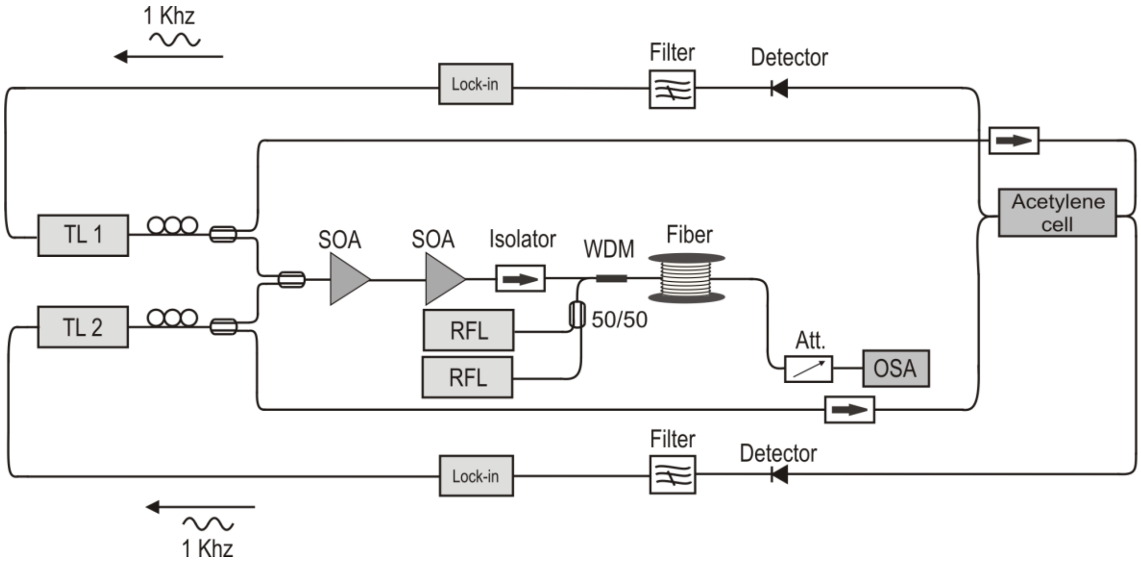

Figure 1.- Experimental setup

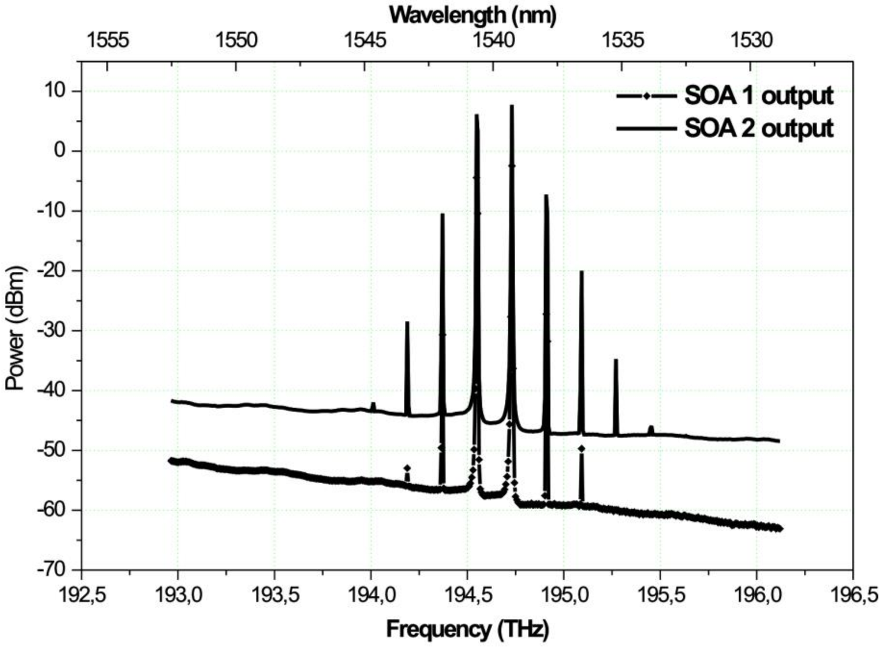

Figure 2- Frequency comb generation: One Raman pump

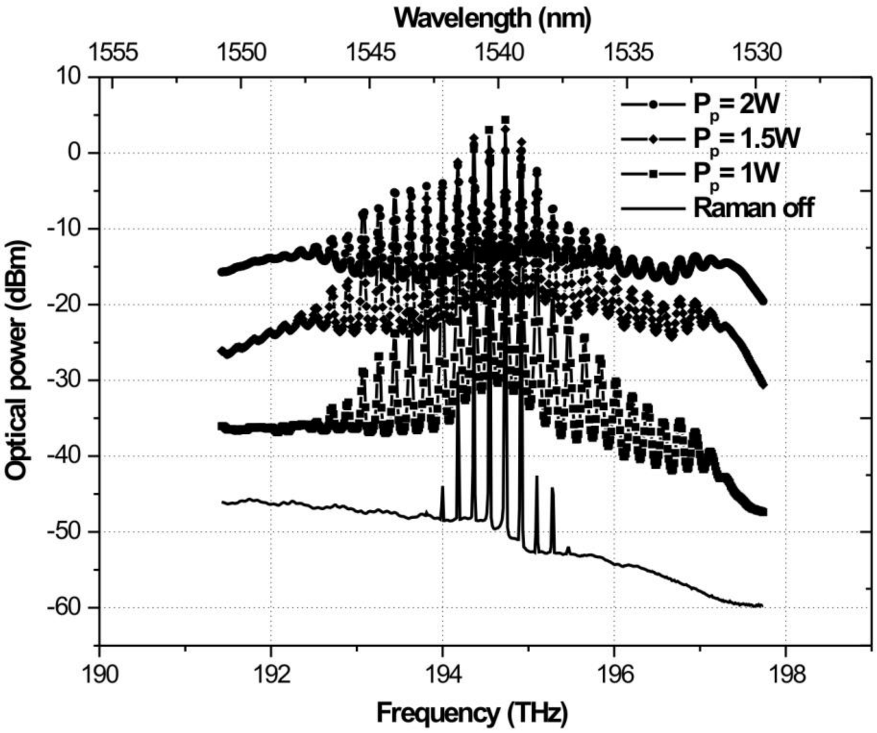

Figure 3- Effect of the pump power in the frequency comb generation

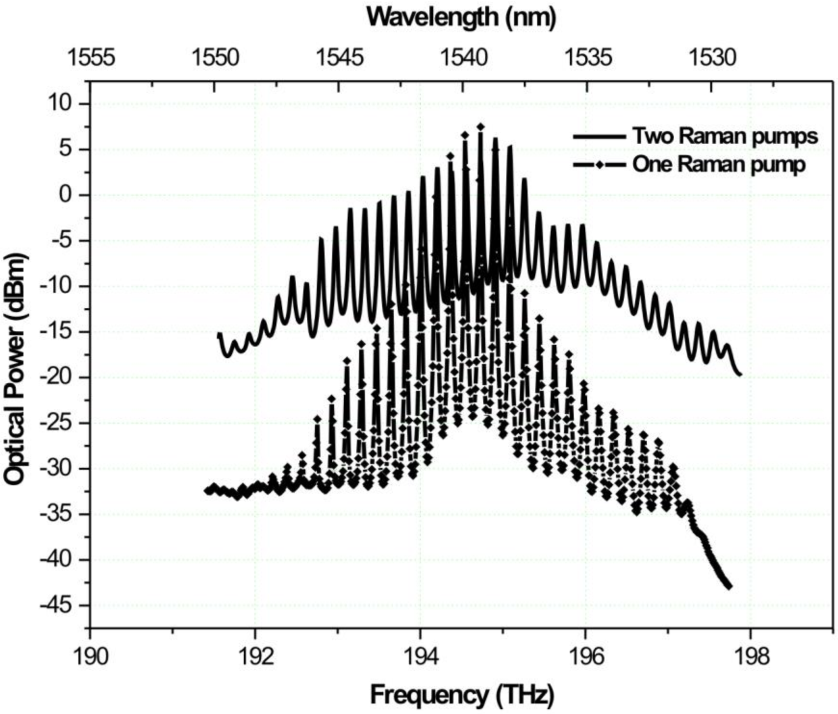

Figure 4.- Frequency comb generation: Two Raman pumps.

TABLE I. - Uncertainty corresponding to the frequency generated at 194.920 THz (k=1)

	F_1		***F_2***	
	Value (GHz)	***Uncertainty (GHz)***	***Value (GHz)***	***Uncertainty (GHz)***
NIST	194742.545	0.007	194565.915	0.019
Δw	0.030	0.017	0.030	0.017
$\sqrt{\sum^2}$		0.019		0.019
f_{FWM}	194920.175	0.033		

TABLE II. - Uncertainty corresponding to the frequency generated at 195.097 THz (k=1)

	F_1 (UNCERTAINTY=F'_{FWM})		F_2	
	Value (GHz)	***Uncertainty (GHz)***	***Value (GHz)***	***Uncertainty (GHz)***
	194920.175	0.033	194742.545	0.007
Δw	0.042	0.024	0.030	0.017
$\sqrt{\sum^2}$		0.041		0.019
f_{FWM}	195097.805	0.061		

TABLE III. - Uncertainty corresponding to the frequency generated at 195.453 THz (k=1)

	F_1 ***(UNCERTAINTY=F''_{FWM})***		***F_2*** ***(UNCERTAINTY=F''_{FWM})***	
	Value (GHz)	***Value (GHz)***	***Value (GHz)***	***Uncertainty (GHz)***
	195097.805	0.061	194920.175	0.033
Δw	0.042	0.024	0.042	0.024
$\sqrt{\sum^2}$		0.066		0.041
f_{FWM}	195453.065	0.102		