Multiplexed optical link for ultra-stable frequency dissemination.

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INTRODUCTION

The transfer of ultra-stable frequency signal between distant laboratories is required by many applications in time and frequency metrology, fundamental physics, particle accelerators and astrophysics [1-8]. Stable radio and microwave frequencies transmission over an optical link has already been demonstrated [3-5,9-12]. Frequency transfer using the optical phase of an ultra-stable laser over a dedicated fiber link was reported on distances up to about 200 km by several groups [13-19]. The present challenge is to extend this technique of frequency dissemination on longer distances in order to connect laboratories of different countries.

For this purpose, we have recently developed a novel dissemination approach over non-dedicated fibers [20]. We take advantage of the existing Internet fiber network, already connecting every laboratories via the National Research Networks (NRENs). The ultra-stable frequency signal is propagating simultaneously with the Internet traffic in the same fiber using one dedicated wavelength in a dense wavelength division multiplexing (DWDM) approach.

With Internet fibers, we have a very limited control on the fiber network and the attenuation and noise is likely to be higher than with dedicated fibers, which can limit the transfer to a few hundreds of km. For longer distances, we have foreseen the segmentation of the link into several cascaded sections. In that case, a repeater station should be used between the different segments of the link. This multiple sub-link approach allows for an increased correction bandwidth and robustness regarding attenuation.

EXPERIMENTAL SET-UP

Figure 1 displays the schema of the repeater station we have developed. The purpose of the Nth station of the link is threefold. First it sends back the incoming optical signal to the previous station (N-1) in order to stabilize the incoming link (named N). Second, a clean-up optical oscillator (low noise fiber laser) is phase locked on the incoming signal in order to regenerate the optical signal and to seed the link departing to next station (N+1). Third, it processes the retroreflected signal from this next station (N+1) allowing for noise compensation of the following link segment (N+1). The station is designed to operate autonomously and with low temperature sensitivity optical interferometers to stand the non-controlled environmental conditions on the link shelters. Moreover, it does not require any stable local reference, since the frequency drift of the local RF oscillator is cancelled by an optimized choice of the local beatnote signal frequencies.

Using this station, we have demonstrated a first implementation of a 300-km cascaded optical link on the French academic and research network (NREN, RENATER).

The overall scheme of the 300 km-long optical link (LPL-Nogent L'Artaud-LPL) with an intermediate repeater station located at Nogent L'Artaud (100 km East of Paris) is depicted in Fig. 2. This link starts and ends at LPL laboratory (at Université Paris 13, in the north surroundings of Paris), and is composed of three different fiber spans. In each span, there are two identical parallel fibers labeled as FU and FD. FU is used for the uplink consisting of 114 km of fiber carrying internet traffic and 36 km of dedicated dark fiber and FD for the downlink with the same characteristics. The first span is composed by two 11 km-long fibers connecting the information service and technology center of Université Paris 13 to a "Data Centre Facility" located in Aubervilliers (Interxion1). The digital stream between Université Paris 13 and Aubervilliers is encoded over an optical carrier on the ITU channel #34 (1550.12 nm) whereas the ultrastable signal is carried by the channel #44, at 1542.14 nm. The second span is composed of two 36 km-long dedicated dark fibers which connect the two "Data Centre facilities" of Interxion 1 and TeleHouse 2, downtown Paris. The third span is composed of two 103 km longhaul intercity fibers simultaneously carrying internet data traffic. In this part the digital data signal are transferred over two channels #42 and #43, only 0.8 nm and 1.6 nm away from the ultrastable signal. At Nogent l'Artaud the reference signal arriving from FU is processed in the repeater station and sent into the other 150 km-long fiber (FD) back to Université Paris 13.

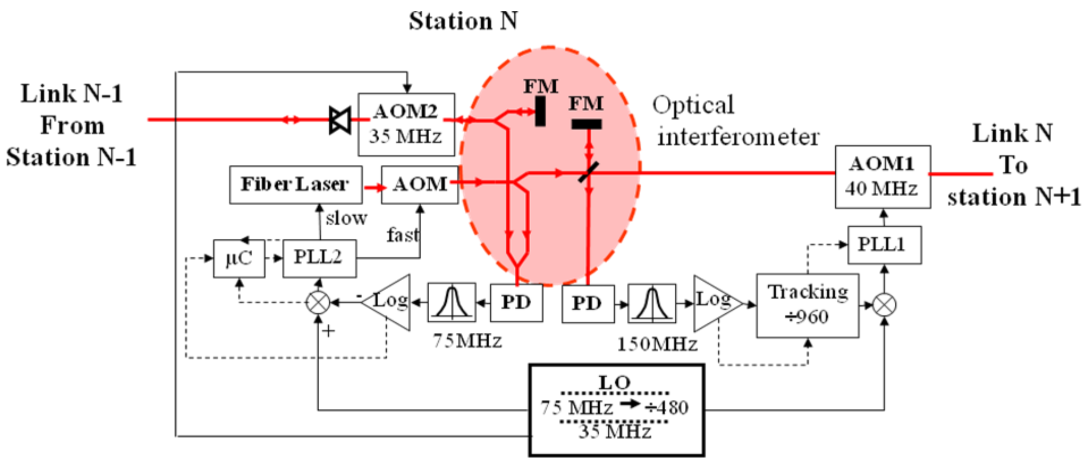

Fig. 1. Schema of the home-made repeater station, FM : Faraday mirror, PD : photodiode, LO : local oscillator, AOM : acoustooptic modulator, Log : logarithmic amplifier, µC : microcontroller, PLL : phase-lock loop

Interconnection between the 36 km-long dark fibers and the optical telecommunication network is not straightforward. Concerning the ultrastable signal transmission, round-trip propagation of the optical signal is required over the same fiber for noise compensation. For that purpose we use bidirectional off-the-shelf optical add-drop multiplexers (OADM). Such three-port component can insert or extract the 1542.14 nm wavelength from the other wavelengths, with isolation better than 25 dB for an adjacent channel (100 GHz) and better than 40 dB for other channels. Eight OADMs are used along the two cascaded link to insert and extract the ultrastable signal. Total attenuation along the link is more than 100 dB due to the large number of connectors and the OADMs. In order to overcome the round-trip link losses, we used four bidirectional Erbium-doped fiber amplifiers (EDFA).

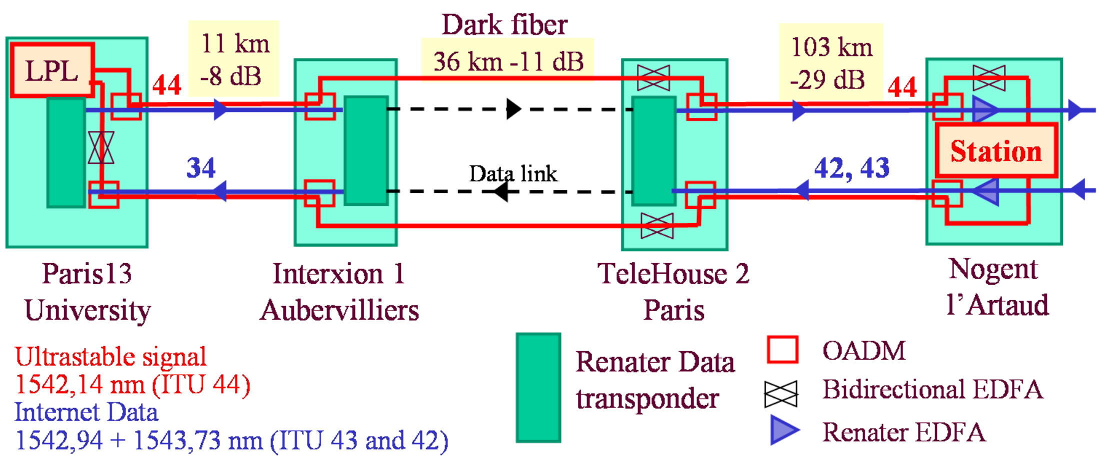

Fig. 2. Schematic setup of 2 x 150 km cascaded optical link. FU, 150-km up-link fiber ; FD, 150-km down-link fiber.

RESULTS

The optical phase noise power spectral density of the cascaded optical link of 2 x 150 km is shown in Fig. 3, without and with compensation. The link phase noise rolls down very sharply after a few hundred Hz. The phase noise reduction is around 50 dB at 1 Hz. For Fourier frequencies below 5 Hz, both spectra exhibit some peaks which are probably due to seismic noise, since the optical are likely to be buried along the railways.

Fig. 4 shows the fractional frequency stability (Allan deviation) of the 2×150 km link for four days of continuous operation, measured with a Π-type frequency counter. The free-running fiber frequency noise is measured simultaneously using the compensation signal (blue circles) applied to the AOM. The Allan deviation is 3×10^{-15} at 1 s averaging time and scales down as $1/\tau$ from 1 s to 70000 s reaching 7×10^{-19} (measurement bandwidth 10Hz). With the full bandwidth (about 300 kHz), the Allan deviation is 6 times larger.

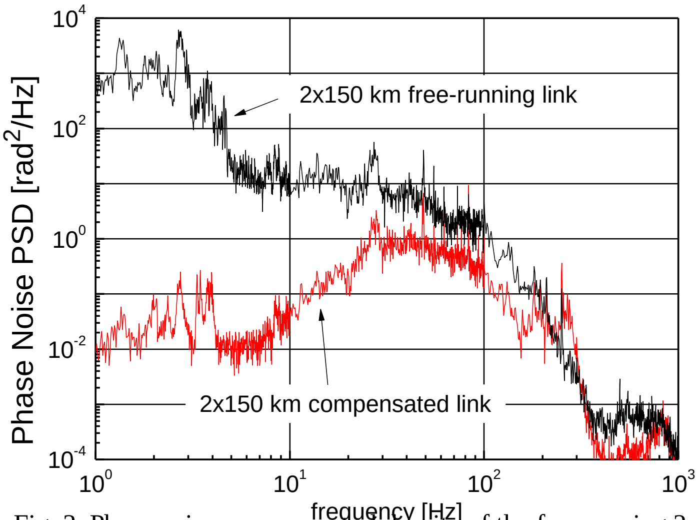

Fig. 3. Phase noise power spectral density of the free running 2×150 km (black line) and compensated 2×150 km link (red line)

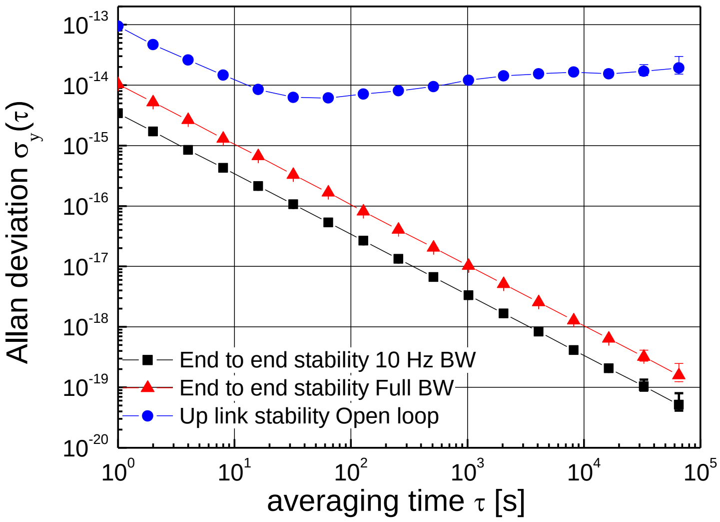

Fig. 4. End-to-end fractional frequency instability of the 2×150 km free running link (blue circles), and compensated link measured without (red triangles) and with a 10 Hz filter (black squares)

CONCLUSION

We demonstrate the ultra stable transfer an optical frequency over 300 km of installed optical fibers. This ultrastable optical link uses an optical telecommunication network simultaneously carrying Internet data and goes through two Data Center Facilities using multiplexers and bidirectional erbium-doped fiber amplifiers. We have obtained an instability of 3×10^{-15} at 1 s which scales down to around 7×10^{-20} after about 20 hours. These results are promising and represent an intermediate step for the future development of continental-scale frequency transfer.

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