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Transmission of Active Optical Reference Signals over a 16 Channel, 534.4 km WDM Optical Fibre Network

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Abstract

Active, optical-transition locked and free-running reference signals have been transmitted over a 534.4 km optical fibre network carrying live traffic. No degradation of the reference wavelength was observed down to the 10^{-8} level although ASE noise and interference signals were observed.

Introduction

Dense wavelength division multiplexed transmission systems (DWDM), based on the ITU defined grid^[i], require frequency stabilization for the individual laser channels, with a control accuracy dependent on the channel spacing^[ii]. Artefact-based solutions have been proposed which are sufficiently accurate for many telecommunication applications^[iii, iv]. Absolute atomic and molecular transition based references are often used to calibrate the monitoring equipment. Certain atomic and molecular transitions are sufficiently close to the ITU grid frequencies that they could be transmitted over an all-optical network, allowing the possibility of accurate frequency dissemination to remote sites. In addition to the network and system applications that require modest accuracies for the optical carrier frequency (of the order of a few parts in 10^{-7}), there are other important metrological applications. Satellite time-transfer is a well-established technique for comparing atomic clocks. Self-referencing optical combs can be used to link the microwave and optical frequency domains, potentially providing much higher accuracies through the use of optical frequency standards. A transparent optical network could potentially be used to link remotely located high-precision standards provided that a suitable all-optical link, with no optical-frequency shifting elements, is available.

Optical references transmitted over a 3.45 km optical fibre link have been previously reported^[v]. In this paper we explore the transmission of active references over a WDM network carrying live traffic. Measurements were also made using passive wavelength references but these results are not presented here. All uncertainties are quoted at the 95% confidence level.

Optical network description

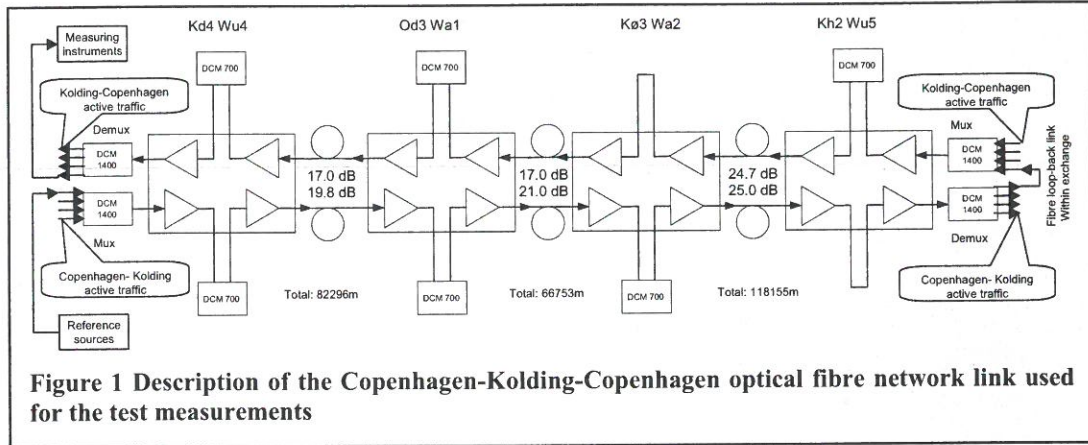
The tests were performed on a network link from Copenhagen to Kolding in Denmark – see Table 1 and Figure 1. During the tests, the network was carrying live traffic. Optical-fibre networks are typically used to provide point-to-point connection only and all switching functions are carried out electronically. Because of this, it was necessary to visit Kolding and install loop-back fibres before taking the measurements.

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Under normal operation, each channel carries an amplitude modulation pilot signalling tone (4 %) in the (10 to 20) kHz range for control and identification of individual channels. However, as the reference standards used in this work are unmodulated they were transmitted at a lower optical power level so that they would not affect the system power-management.

Transmission of active references over the network

Table 1. Network parameters of the Copenhagen - Kolding - Copenhagen optical fibre network link used for the tests		
Number of Channels	16 total, 7 in active use	
WDM channels	200 GHz spacing, 80 GHz bandwidth, C-band (1530-1565) nm	
Channels available	195.1 THz (1536.609 nm) 193.5 THz (1549.315 nm)	
Amplifiers	8 Dual stage, 1 Single stage	
Fibre losses (round-trip)	Copenhagen-Kolding	58.7 dB
	Kolding-Copenhagen	65.8 dB
	Total	124.5 dB
Dispersion compensation	4 x 1360 ps/nm, 6 x 680 ps/nm. (9520 ps/nm total) equivalent to 560 km of G.652 single-mode fibre.	
Residual chromatic dispersion	-25.6 km (round trip) equivalent to 448 ps/nm	
Total length	534.4 km	

Transmission of an active reference is representative of the signals normally present within the network. The reference^[vi, vii] comprised an Er/Yb-doped, temperature tuned, optical fibre laser with an inscribed Bragg grating to provide optical feedback, locked to the Doppler-broadened P26 line of ¹³C acetylene (v1+v3) in a 100 mm cell, at a pressure of 5.0 kPa, giving a nominal line-centre wavelength of 1548.819316 nm at 324 μW. The transmitted reference and active channels signals, measured using an optical spectrum analyser, are shown in Figure 2.

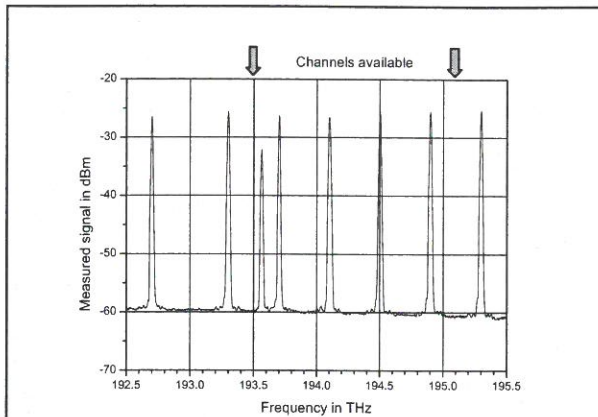


Figure 2 Transmission of Er/Yb fibre-laser reference locked to the Doppler broadened P26 ^{13}C acetylene line on the channel at 193.5 THz. The reference optical power is approximately 10 dB below the typical channel power.

The wavelength of the locked laser was measured with a wavelength meter both before and after transmission through the network. Two full cycles were taken over a 75-minute period and each measurement set comprised 350 readings, measured as groups of 10 measurements per point. The resolution and stability of the wavelength meter is more important than its absolute calibration accuracy because we are considering the difference between the wavelength measured directly and the wavelength transmitted through the network. However, in the analysis, the main uncertainty contribution is due to the numerical resolution of the instrument.

The laser remained locked to the acetylene reference during the measurements but

dropped out of lock shortly after the measurements were completed, due to the high temperature within the telephone exchange environment. Consequently, the rate of drift of the optical frequency with time is important. The measured results are shown in Figure 3 and

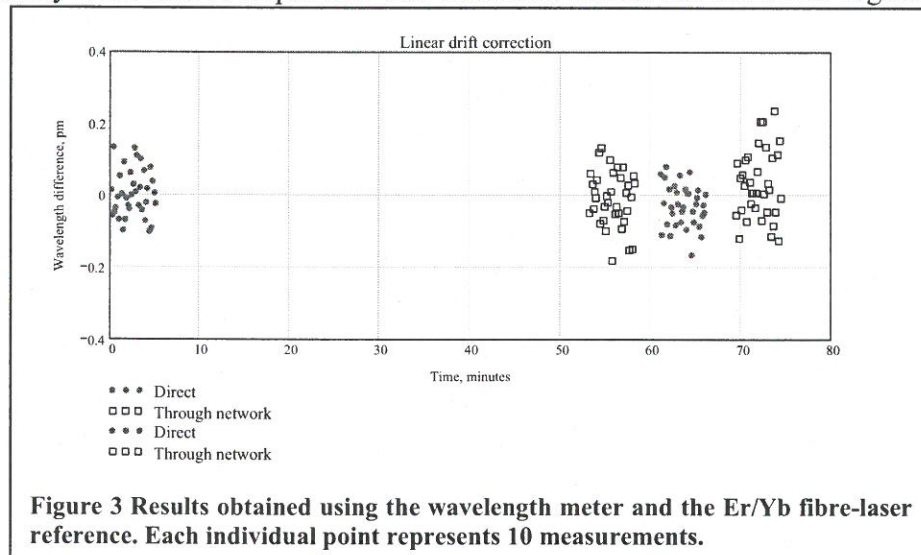


Figure 3 Results obtained using the wavelength meter and the Er/Yb fibre-laser reference. Each individual point represents 10 measurements.

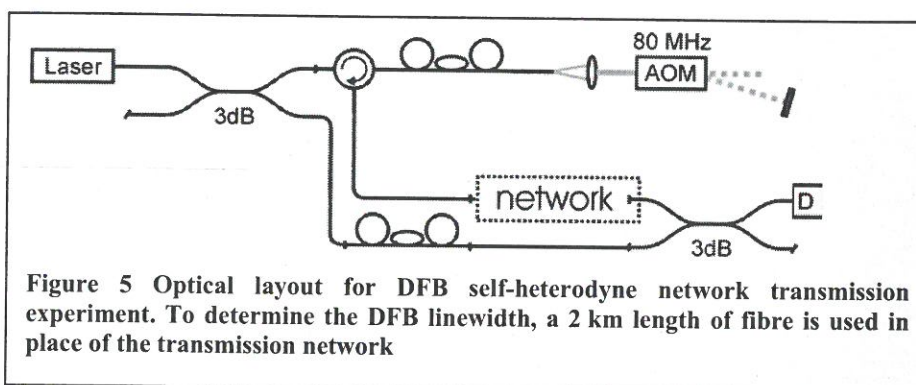
have been analysed as an ABA comparison, taking the average linear drift-rate into account (see Table 2). These results suggest that any frequency shifts or interference is smaller than the instrument resolution.

Delayed self-heterodyne measurements

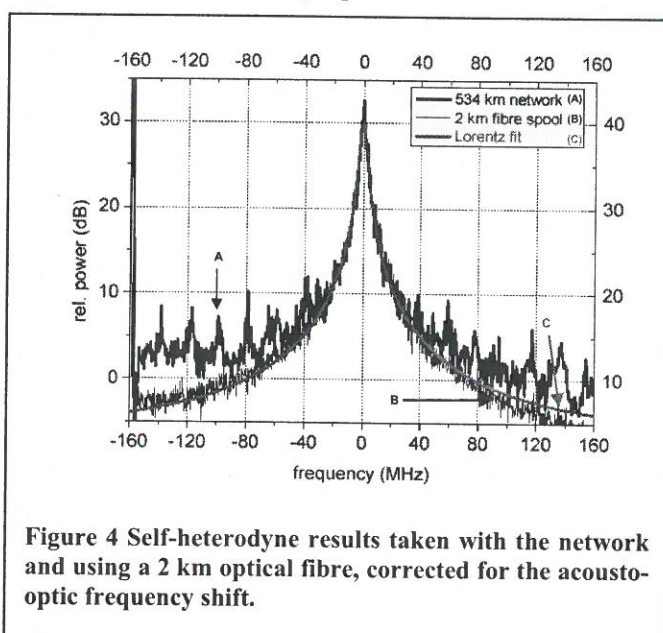
The delayed self-heterodyne technique provided the highest resolution measurements to test for frequency broadening and frequency shift. In essence, the system (shown in Figure 4) forms a Mach-Zehnder interferometer with either the network or a 2 km dummy fibre as

Table 2 Analysis of network transmission results for P26 ^{13}C Acetylene locked reference

	Drift rate kHz/s	A-B-A comparison, corrected for linear drift (MHz)
Direct (D1-D2)	-1.77	D1-N1-D2 -1.66±10.7
Network (N1-N2)	-8.04	N1-D2-N2 +4.59±11.0



one of the interferometer arms. The second arm of the interferometer comprises a short length (<10 meters) of single-mode optical fibre and a polarization controller to optimise the heterodyne beat signal. Commercial 50:50, single-mode fused couplers serve to divide and recombine the laser light. Despite the length of the optical fibre network link, the polarization state of the light, transmitted over the network, drifted quite slowly and so the heterodyne signal could be manually optimised.



A commercially available DFB-laser module was used for the experiment together with a low-noise current supply and temperature controller developed at PTB. The system shows frequency fluctuations and drift below 10 MHz (rms) over 1 hour. The laser was operated at (9.7 ± 0.2) mW and displays a Schawlow-Townes limited laser linewidth with a Lorentzian line-shape.

The light transmitted through the network/fibre was frequency shifted using a circulator and an acousto-optic-modulator in a double-pass configuration, giving an RF spectrum centred at 160 MHz. The heterodyne beat was analysed using a fibre-

coupled, amplified InGaAs photodiode and an RF spectrum analyser. A Lorentzian curve was fitted to the measured results over a ± 50 MHz range about the peak. The measured spectra are shown in Figure 5, together with the Lorentzian-fit to the dummy fibre results. The Lorentzian-fitted beat-width results for the network and the dummy fibre are both about 4 MHz (see Table 3). This simply reflects the laser linewidth and indicates that no frequency shift or broadening of the laser linewidth was detected within the measurement uncertainty of ± 0.4 MHz (2×10^{-9}).

Table 3 Summary of self-heterodyne results

	Centre frequency (MHz)	Beat width (MHz)
534 km Network	-0.054 ± 0.2	3.82 ± 0.4
2 km fibre-spool	-0.054 ± 0.1	4.29 ± 0.2

Discussion

The results show that optical references can be successfully transmitted or distributed over an all-optical network with an accuracy of better than 10^{-8} . This is easily sufficient for remote calibration of common measuring equipment and for monitoring purposes within a telecommunication networks.

The results obtained using a wavelength meter show that input and transmitted signals agree to within $<10^{-8}$, with an uncertainty of 5×10^{-8} , and are limited by the performance of the instrument.

The DFB self-heterodyne measurement gives approximately an order of magnitude accuracy improvement over the wavelength meter. In this experiment, the upper limits for line-broadening and frequency shift of the transmitted signal are 2×10^{-9} . Again, this limiting value is set by the resolution of the experiment, which is mainly due to the laser line-width. Additional optical noise and interference contributions, possibly caused by a four-wave mixing process, were at least 20 dB below the carrier signal.

No Stimulated Brillouin Scattering (SBS) power saturation effects were observed even though the optical references used for the transmission experiments had linewidths that were less than the SBS transition width.

Acknowledgements

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