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Raman amplification for ultra-stable coherent frequency transmission in S band

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Abstract. In this paper, we provide overview of deployed wavelengths for long haul ultra-stable coherent frequency dissemination. Based on effort to eliminate noise caused by parallel data transmission, we are proposing to utilize the S band. Suitable ways of optical amplification are discussed, and the most promising Raman amplification is chosen for deeper investigation.

1. Introduction

There has been further progress recently in the area of time and frequency (T&F) metrology, and also in applications benefiting from the highest possible precision; for example in fundamental physics, geodesy, telecommunication, industry that require time and frequency reference signals with significantly higher performance than is currently mediated by satellite techniques. Very high performance time and frequency reference signals are also moving from radio signal broadcasting to be transported over optical fiber networks as the development of relevant technologies for T&F transfer on optical links progresses rapidly. However, widespread utilization of such signals is currently hampered by a lack of sustainable and reliable infrastructure. Nevertheless, due to all the benefits, optical fiber links for T&F are being actively developed and operated by Japan, China, US and as well in Europe, where these include cross-border fiber links. To foster the innovative approach, since 2017, there has been European project CLONETS [1] which aims to prepare the conditions where these links may be combined and completed to form a pan-European network, with a sustainable organization allowing it to operate as a long term service not only to research infrastructures but also for industry and society.

2. Optical infrastructure CESNET

CESNET association (provider of e-Infrastructure for research and education in the Czech Republic) is continuously developing the optical part of infrastructure to fulfil the data transmission capacities the users very need, yet also to benefit from the wide range of research possibilities the spectrum within shared fiber enables. Time and Frequency (T&F) infrastructure is a part of the above mentioned optical infrastructure, with first international time transfer line over Cross Border Fiber (CBF) established 2011, for details see [2] and [3]. Important component of the infrastructure is optical frequency part. As the T&F infrastructure preferably shares fiber infrastructure with regular data transmissions network, it allows to cope with high fiber rental costs [4], especially when enlarging the infrastructure according to the needs. Such infrastructure allows parallel transmission of accurate time and stable frequency distribution based on wavelength division multiplexing (WDM). Optical frequency is coherently transferred as a Continuous Wave (CW) signal with active noise cancelation,

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described e.g. in [5]. Two lines are being operated in the Czech Republic: Brno – Prague, extended to Řež (shown in red in Figure 1) and the other one is Brno – Temelín, the nuclear power plant (shown in orange in Figure 1), for details please see [2], [6]. Both lines were designed for distribution of optical frequency among stationary laser standards located at endpoints. Standards are based on saturated absorption in vapors of acetylene $^{13}C_2H_2$. They use fiber laser with a very narrow linewidth (<100 Hz) operating close to wavelength of channel #46 1540.56, for detail see [2]. This exact absorption line was chosen because of its good correspondence to telecommunication wavelength grid defined by ITU Telecommunication Standardization Sector (ITU-T).

Figure 1. Coherent optical frequency dissemination infrastructure

3. Transmission band selection

Coherent optical frequency transfer can deliver outstanding transmission stability ([7]-[9]), and it has been undergoing significant number of field deployments recently. Majority of teams start to use channel #44 1542.12 nm. However, in scenarios with parallel data transmission using amplitude modulation (AM) and now quadrature amplitude modulation (QAM), coherent CW transfer of optical frequency tends to be sensitive to the phase noise, and presences of AM signal in spectral proximity increase such noise [4]. In order to limit phase noise, dark channel was proposed to utilize unused part of spectrum out of the Conventional – (C) band (covering 1530 nm – 1565 nm). For example, VSL transmission related group [10] is using 1510 nm band. Unfortunately, this band is also used by supervisory channel of DWDM transmission system which is also AM. The possible candidate is Long (L) band (1565 nm – 1625 nm) or Short S band (1450-1530 nm). L band is considered by other network operators, because it can be amplified by Erbium Doped Fiber Amplifiers (EDFA) which caused real revolution in the field of optical amplification in late 1980s when amplifiers based on rare-earth elements were commercially available [11]. The most important of all rare-elements for telecommunication fiber networks is Erbium, because it can amplify signals in the most important frequency spectra in silica fiber –C band. EDFAs covers1530 nm – 1565 nm, and can also be customized to amplify signals in the L band covering 1565 nm – 1625 nm. They represent mature widespread used technology. As with any real devices, optical amplifiers have some limiting factors in practical deployment. The most important issue is amplifier noise, usually expressed as Noise Figure (NF).

For our purpose, there remains S band 1460-1490nm, still in low loss window of single mode fiber. For S band, there is very suitable rare element Thulium; however glass matrix must in this case contain fluoride. Unfortunately, Thulium doped fiber amplifiers haven't been used commercially as fluoride fibers cannot be spliced with standard silica based, and are hydroscopic. Thulium amplifiers also suffer from lower efficiency and higher NF compared to EDFAs [11]. Semiconductor optical amplifiers (SOA) are next possible solution for optical amplification; an excellent review can be found for example in [12]. In telecommunication networks, SOAs were deployed in 1980s even with some drawbacks like rather high noise figure and polarization sensitivity, and also serious problems when

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amplifying more than one signal due to effects like cross phase modulation. On the other hand, SOAs can be manufactured in specific ways and are able to work almost in every optical band, covering S band and they can even be integrated on chips. SOAs are suffering by problem with multiple signals amplification, so they are used unidirectional [ref Jeroen] breaking demand to single propagation path. Lumped amplifiers, e.g. rare element based amplifiers (e.g. EDFAs) and SOAs can provide only limited gain in bidirectional scenarios with reflective environment [13], as their feedback causes unwanted oscillations. Also natural Rayleigh back scattering increases such feedback.

Raman amplification based on stimulated Raman inelastic Scattering (SRS) can provide another principle used for optical amplification. This process is rather different from stimulated emission, where incident photons stimulate emission to another photon with the same energy (i.e. frequency). In SRS, incident photons create other photons, but with lower energy (i.e. with lower frequency), and the remaining energy is absorbed in the fiber glass as molecular vibrations (so called optical phonons). Raman amplification is very different to EDFAs, Thulium DFAs and SOAs – the transmission fiber itself is used as the media for amplification. The Raman effect in silica fiber is broadband but relatively weak, and much higher pump powers are required compared to EDFAs, polarization dependency can be solved with the use of two orthogonally polarized pump sources. Raman amplifiers have been proposed and verified for ultra-stable frequency e.g. [14] and [15], however due the presence of high pump powers they are not suitable for fibers with simultaneous data transmission.

4. Distributed Raman Amplification

Distributed Raman Amplification (DRA) can be conveniently and with advantage deployed for enlargement of desired distance, neglecting partially the fiber attenuation. Unfortunately, the pump signal is also attenuated when propagated in fiber. It poses limit to achievable distance enlargement, especially in standard telecommunication fibers depending on G.652 where the Raman gain coefficient is low and maximal pump power is limited by used optical connectors.

Pump power decreases in transmission fiber as pump propagates, until it falls under some threshold level. Evolution of pump power is described in Eq. (1):

$$P_p(z) = P_0 \cdot \exp(-\alpha_p \cdot z) \qquad (1)$$

P_0 is pump input power and α_p is fiber attenuation at wavelength of pump. In practical situation when signal power satisfies small signal condition P_p>> Ps, we can neglect pump depletion and describe signal evolution by Eq. (2):

$$P_s(L) = P_s(0) \cdot \exp(g_r \cdot P_0 \cdot L_{eff} - \alpha_s \cdot L) \qquad (2)$$

g_r is Raman gain coefficient, α_s is fiber attenuation at signal wavelength and L_{eff} is given by Eq. (5):

$$L_{eff} = \alpha_p^{-1} \cdot [1 - \exp(-\alpha_p \cdot L)] \qquad (3)$$

By differentiation of Eq. 3, we can determine optimal fiber length L_{opt}. This signal undergoes amplification and its level increases till this length L_{opt}, and after its signal starts to decrease because of attenuation.

$$L_{opt} = -\alpha_p^{-1} \cdot \ln(\alpha_s \cdot g_r^{-1} \cdot P_0^{-1}) \qquad (4)$$

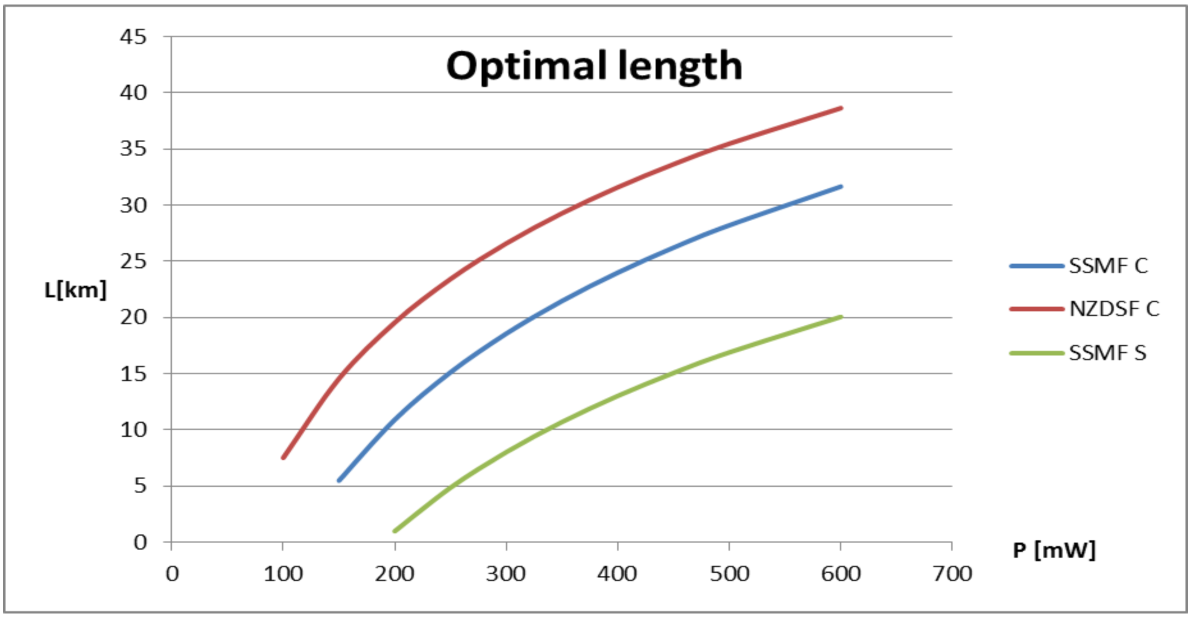

Figure 2. Optimal lengths for distributed Raman amplification in different fibers

Using Eq. (4) and typical values of α_p, α_s and g_r for standard single mode fiber (SSMF) and non-zero dispersion shifted fiber (NZDSF), we can determine L_{opt} for different pump powers. Figure 2. illustrates good effectivity of Raman pumping in NZDFS in C band (red curve), especially due to high g_r. Effectivity of Raman pumping is lower in SSMF in C band due to lower g_r (blue curve). In one of our previous work [16] we achieved on-off gain in C band 13.2 dB for 500 mW of pumping. Unfortunately, Raman pumping in S band suffers from very low efficiency due to slightly higher signal attenuation, and especially due to high attenuation at pump wavelength 1350 nm (green curve) even such wavelength is outside of depreciated OH^- absorption peak.

5. Conclusion

In this paper, we provided overview of deployed wavelengths for long haul ultra-stable coherent frequency dissemination over Europe by different groups. Based on our effort to eliminate noise caused by parallel data transmission, we proposed to utilize the S band. Suitable ways of optical amplification were discussed, and the most promising Raman amplification was chosen for deeper investigation. Unfortunately increased losses in S band (both signal and pump) will lead to very low efficiency, with estimated gain of about 8 dB for 500 mW pumping. Due to this fact we decided to choose SOA for next experiments.

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References

[1] Vojtěch et al., "The H2020 Project CLONETS: Clock Services over Optical-fibre Networks in Europe," 2018 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, 2018, pp. 1-2.
[2] Vojtech, J., Slapak, M., Skoda, P., Radil, J., Havlis, O. et al., “Joint accurate time and stable frequency distribution infrastructure sharing fibre footprint with research network,“ Opt. Eng. 56(2), 027101 (2017). doi:10.1117/1.OE.56.2.027101.
[3] Smotlacha, V., Vojtěch, J. and Kuna, A., "Optical infrastructure for time and frequency transfer," 2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC), Prague, 2013, pp. 481-484.doi: 10.1109/EFTF-IFC.2013.6702170

[4] Munster, P. et al., “Interference of Data Transmission in Access and Backbone Networks by High-Power Sensor System,” Fiber and Integrated Optics 36(3), pp. 144-156, (2017). doi.org: 10.1080/01468030.2017.1327624.

[5] Cizek, M., et al., "Transfer of stable optical frequency for sensory networks via 306 km optical fiber link," 2016 European Frequency and Time Forum (EFTF), York, 2016, pp. 1-4. doi: 10.1109/EFTF.2016.7477821.

[6] Vojtěch, J., et al., "Joint stable optical frequency and precise time transfer over 406 km of shared fiber lines — Study," 2017 40th International Conference on Telecommunications and Signal Processing (TSP), Barcelona, 2017, pp. 694-697. doi: 10.1109/TSP.2017.8076076.

[7] S. Droste, F. Ozimek, Th. Udem, K. Predehl, T. W. Hänsch, H. Schnatz, G. Grosche, and R. Holzwarth: Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link, Physical Review Letters 111, 110801 (2013).

[8] Lopez, O., Kanj, A., Pottie, P. E. et al, "Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network," Appl. Phys. B, vol. 110, no. 1, pp. 3–6, (2012).

[9] Calonico, D. et al, "Optical frequency transfer with a 1284 km coherent fiber link," Proc. EFTF, pp. 1-4, (2014).

[10] Dierikx, E. F., Dierikx, A. E., Fordell, T., Myyry, J., Koponen, P., Merimaa, M., Smets, R. (2016). White Rabbit Precision Time Protocol on Long-Distance Fiber Links. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 63(7), 945-952. DOI: 10.1109/TUFFC.2016.2518122

[11] Becker, P.C., Olsson, N.A. and Simpson, J.R. , "Erbium-Doped Fiber Amplifiers, Fundamentals and Technology ", ISBN: 978-0-12-084590-3, 1999.

[12] Dutta, N. K., Wang, Q., "Semiconductor Optical Amplifiers", ISBN 981-256

[13] Vojtech, J., et al., "Multi-purpose infrastructure for dissemination of precise stable optical frequency", Proc. SPIE 10765, Infrared Remote Sensing and Instrumentation XXVI, 1076507 (18 September 2018); doi: 10.1117/12.2321333.

[14] 17 Clivati, C., "Distributed Raman Amplification for long-haul optical frequency dissemination," Proc. IFCS-EFTF-SPC, 184 (2013).

[15] Vojtech, J. and Smotlacha, V., "Precise time transfer infrastructure over heterogeneous fibre environment," 2014 16th International Conference on Transparent Optical Networks (ICTON), Graz, 2014, pp. 1-3. doi: 10.1109/ICTON.2014.6876488

[16] V. Smotlacha and J. Vojtěch, "Time and frequency transfer using amplified optical links," 2014 European Frequency and Time Forum (EFTF), Neuchatel, 2014, pp. 325-328. doi: 10.1109/EFTF.2014.7331500