Noise filtering in a multi-channel system using a tunable liquid crystal photonic bandgap fiber

Martin Nordal Petersen,[1] Lara Scolari,[1,*] Torger Tokle,[2] Thomas Tanggaard Alkeskjold,[3] Sebastian Gauza,[4] Shin–Tson Wu,[4] and Anders Bjarklev[1]

[1]*DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads 343, DK-2800 Kgs. Lyngby, Denmark*
[2]*OFS Fitel Denmark ApS, Priorparken 680, 2605 Brøndby, Denmark*
[3]*Crystal Fibre A/S, Blokken 84, 3460 Birkerød, Denmark*
[4]*College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA*
[*]*Corresponding author: lsco@fotonik.dtu.dk*

Abstract: This paper reports on the first application of a liquid crystal infiltrated photonic bandgap fiber used as a tunable filter in an optical transmission system. The device allows low-cost amplified spontaneous emission (ASE) noise filtering and gain equalization with low insertion loss and broad tunability. System experiments show that the use of this filter increases for times the distance over which the optical signal-to-noise ratio (OSNR) is sufficient for error-free transmission with respect to the case in which no filtering is used.

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1. Introduction

Photonic Crystal Fibers (PCFs) [1,2] have a microstructure which allows the realization of either the high-index guiding principle, which guides light in a high-index core similarly to the total internal reflection principle, or the bandgap-guiding principle, which guides light in a low-index core by means of coherent reflections from the surrounding periodic structure [3]. The presence of air holes in the structure also gives the possibility to infuse liquids and, therefore, to create tunable devices [4-6]. Among liquid materials, liquid crystals represent a very good candidate for the fabrication of tunable all-in-fiber components because they exhibit very high electro-optic and thermo-optic effects due to high birefringence (Δn~0.8) [7] and large dielectric anisotropy ($\Delta\varepsilon$~ 70) [8]. If silica index-guiding PCFs are infiltrated with liquid crystals, they start guiding light by the bandgap effect, because liquid crystals have refractive indices higher than that of silica. Based on Liquid Crystal filled PCFs (LCPCF), devices which can be thermally, electrically or optically tuned, have been demonstrated [9-20]. Among these, we find, for example, devices for tuning, scrambling and controlling the polarization [11,19], tunable Gaussian filters for Optical Coherence Tomography (OCT) [14], tunable electrically and mechanically induced gratings [15], tunable notch filters [16], devices with tunable birefringence [18] and for single-polarization and high-birefringence guidance [20].

Optical transmission systems are currently moving more and more towards transparent optical networking. This includes optical switching, optical adding and dropping as well as fewer optical-electronic-optical conversions in the network. Generally speaking, this means transmitting over longer distances while still keeping the signal in the optical domain. While transparent optical networking offers several advantages, it also carries the increasing problem of accumulated noise caused by the rising number of erbium doped fiber amplifiers (EDFAs) in the optical transmission line. Additionally, noise in the signal band will embezzle gain from the signal wavelengths and through amplifier cascading the problem increases and eventually leads to the EDFAs being saturated by noise while the channel power decreases below noise level [21, 22].

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In today's systems the excess noise is typically reduced by using gain flattening filtering (GFF) [23, 24]. Alternatively, the out-of-band noise can be removed in reconfigurable optical add-drop multiplexers.

In this paper we present the first application of a LCPCF device in optical communication systems. We implement a very compact all-optical high-pass filter with only 5 dB insertion loss (including splice losses). Through temperature tuning of the liquid crystal, the filter transfer function can be adjusted to minimize the amplified spontaneous emission (ASE) noise peak in the spectrum while assuring low transmission loss and gain equalization for the data channels.

We present experimental results where this filter is used to extend the maximum transmission distance. The filter allows four times longer transmission distance compared to a case without a filter. The experiment shows that LCPCF-based devices are suitable for optical communication systems.

2. Operational principles

An optical communication system is made up of several transmission spans and EDFAs for amplification. In such a system, amplified ASE noise will give rise to a noise peak at around 1530 nm, where the location of the maximum ASE noise peak depends on the particular EDFA configuration [25]. The buildup of an ASE peak is illustrated in Fig. 1 where four channels have been transmitted 10 spans of each 65 km and where the signals have been amplified after each span using EDFAs. The dotted line illustrates a situation when the signals are amplified after each span without noise filtering, and as can be seen the optical-signal-to-noise-ratio (OSNR) has dropped below any acceptable limit and the signals would be unrecoverable. The channel at the longest wavelength has completely disappeared below the noise level (Fig. 1, red curve). This happens as the EDFAs will eventually get saturated from the great amount of power concentrated in the noise peak and thus leaving behind the channels with a highly reduced gain. In the example above, the optical power into each of the amplifiers receiving the signal is -12 dBm.

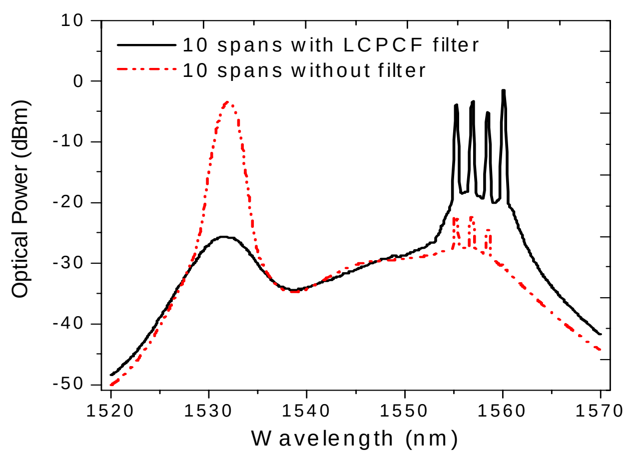

Fig. 1. Optical power spectrum after 10 spans with and without the LCPCF filter. Without filtering, a large ASE peak is created at 1530 nm and the signals drown in noise.

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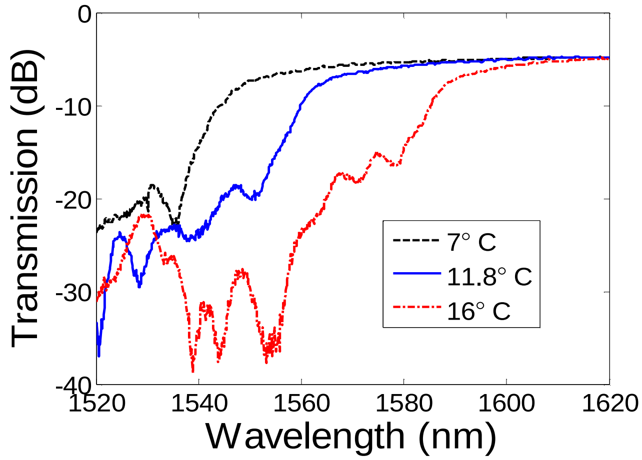

Fig. 2. Transfer curve (filter shape) of the LCPCF filter for three different temperatures. The length of the PCF is 50 cm and the LC infiltrated region is 10 mm.

If instead a LCPCF filter is inserted at the amplification points, the noise power is reduced considerably (Fig. 1, black/full-line curve) and the channels now sustain an OSNR higher than 15 dB after the same distance, which is enough for error free detection assuming a forward-error-correction scheme is used. In this example, the filter temperature was 11.8 °C. In Fig. 2 the transfer curves for various filter temperatures are shown. The tunability is given by the change of the LC refractive indices as a function of temperature.

3. Experimental results

PCFs infiltrated with liquid crystals have previously been reported [9-20], but never before found applications within telecommunications. Figure 3 (bottom) illustrates the physical layout of the LCPCF fiber. A piece of 50 cm PCF fiber was filled by using capillary forces, for approximately 10mm, with a custom made high birefringence liquid crystal designated as UCF1 [26] and mechanically spliced to a standard single mode fiber by using a silica ferrule. The empty PCF is high-index guiding and becomes band-gap guiding when the fiber is UCF1 infiltrated. Stop-bands appear in the transmission spectrum, therefore giving the opportunity to use the device as an optical filter. A UV curable polymer was positioned around the ferrule and UV cured in order to give mechanical stability to the device. The filter was then mounted on a Peltier element in order to vary the temperature of the liquid crystal and, therefore, provide thermal tunability to the transmission spectrum. The filter fabricated for this application allows full tunability over the C- and L-band. The tunability is useful in both the perspective of assuring maximum suppression of the ASE noise but also to optimize the gain equalization features provided by the filter. The setup shown in Fig. 3 was used to experimentally demonstrate the effect of noise filtering and gain equalization by using the LCPCF filter. Four laser diodes (LD) were used to produce four channels in the spectral range from 1555 nm to 1560 nm. After amplification the channels were transmitted to the loop controller which filled up a loop consisting of 44 km standard single mode fiber (SSMF), two EDFA amplifiers and the LCPCF filter. The configuration with two amplifiers is common in transmission systems where dispersion compensation is necessary and thus used to overcome the loss in the dispersion compensating fiber (DCF). In this case DCF has not been inserted as there is no data modulation on the channels, which is not necessary since we are using OSNR to evaluate the method and OSNR is not influenced by chromatic dispersion. Although not using any DCF modules, the double-amplifier configuration is applied in order to have more freedom in terms of power-variation when evaluating the device. Noise, on the other hand,

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will have a direct impact on the OSNR and thus makes it an ideal evaluation parameter for this demonstration.

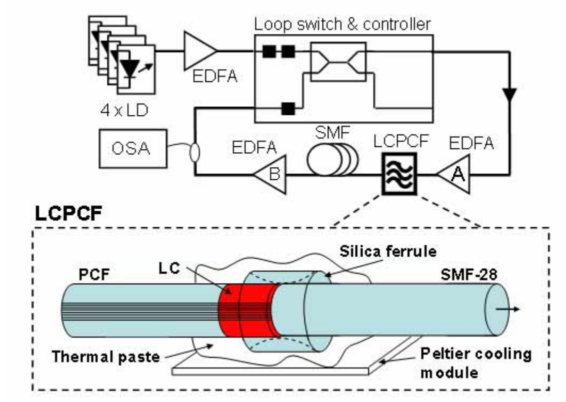

Fig. 3. Experimental loop setup used to demonstrate LCPCF noise filtering. The bottom enlargement illustrates the physical layout of the LCPCF filter.

In the experimental investigations, the LCPCF was inserted between EDFA "A" and "B" as depicted in Fig. 3. With an insertion loss of only 5 dB the LCPCF filter will only have a modest impact on the system losses. An optical attenuator was placed after the SSMF and used to vary the input power to EDFA "A" and thus simulate changing lengths of transmission fiber. Since OSNR is used for evaluation, this will have the same effect as changing the length of transmission fiber. The optical spectrum analyzer (OSA) also inserted in the loop is used in order to evaluate the OSNR of the signals after a pre-selected number of round trips (spans) in the loop. By triggering the OSA with the switching signals from the loop controller any number of round trips can be selected.

Using this setup a set of experiments was carried out in order to experimentally validate the effect of noise filtering using the LCPCF high pass filter. In the first set of experiments the number of loops was fixed to 10 spans while the span-length was varied from 10 km to 85 km corresponding to a span loss between 3 dB and 18 dB. This was done for both the case without filtering and with LCPCF filtering at each span. Results are shown in Fig 4 where the two curves represent the average OSNR value of all channels for each case.

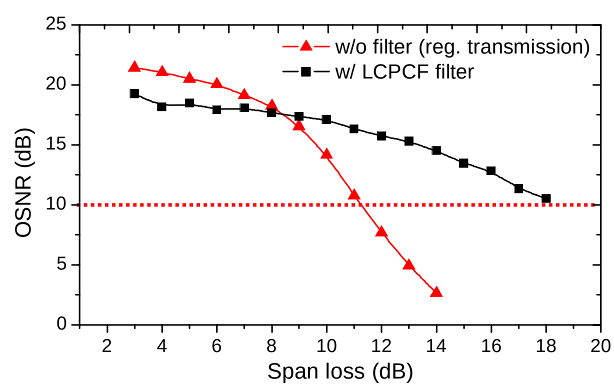

Fig. 4. Results of OSNR vs. span-loss investigation without filtering and with the LCPCF filter. The number of transmitted spans was fixed at 10.

First of all, one can see from the figure that the filter has little or no positive effect when the span loss becomes less than 8 dB (40 km). When the span loss is less than 8 dB there is not enough noise generated for the LCPCF filtering effect to be effective. Instead the LCPCF

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leads to excess noise due to the filter insertion loss and this in turn leads to a 3 dB OSNR penalty. If the losses exceed 8 dB (40 km SSMF) the situation changes as the filter now becomes effective in reducing the noise peak at 1530 nm. If a limit at OSNR = 10 dB is considered, corresponding to a BER of minimum $1x10^{-9}$ using a proper FEC coding at a bit rate of 10 Gbit/s, the improvement from using the filter is a 7 dB increase in maximum span loss. Thus the span length can be increased by 35 km compared to the situation without the LCPCF filter. Alternatively, if a fixed span length of e.g. 65 km is specified, a system without the filter would suffer from an OSNR of 5 dB whereas using the LCPCF filter would achieve an OSNR of 15 dB.

In the second set of experiments the span length was fixed to 80 km corresponding to a span loss of 16 dB. While keeping the span loss constant, the number of transmitted spans was increased and the OSNR of all channels evaluated after each span. This was done for both the case without filtering and with LCPCF filtering inserted at each span. Results are shown in Fig. 5 where the two curves again represent the average OSNR value of all channels for each case. It can be seen from the results that with this fixed span length of 80 km, the LCPCF has a beneficial effect on the OSNR for any number of spans. Without a filter, the OSNR-performance is very poor as the OSNR drops below 10 dB already after 5 spans. If the LCPCF filter is inserted, the maximum transmission increases to at least 20 spans – a significant improvement of 15 spans or 1200 km. Thus, in this example the LCPCF filter enables transmission distances over four times as long. A last interesting point to mention is related to the production costs of a LCPCF filter, which has the potential of being very low due to the simplicity of the filter. An estimate of the material cost per filter produced for this demonstration is in the order of a few dollars.

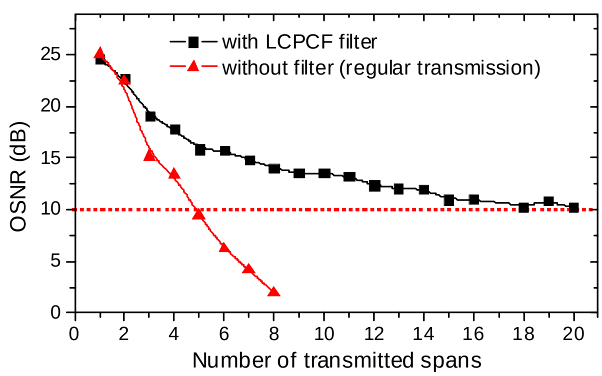

Fig. 5. Results of OSNR vs. number-of-spans investigation without filtering and with the LCPCF filter. Each span here is of fixed length 80 km.

4. Conclusions

This paper presents a novel use of a broad tunable LCPCF filter that enables very low cost effective noise filtering in a multi-channel system. The transmission spectrum of the LCPCF filter displays a minimum that is ideal for removing the ASE noise peak often observed around 1530 nm. Despite the loss of 5 dB, the benefit of filtering is dramatic as seen from the experimental results. Using this filter, the transmission distance is extended by a factor of 4 from 400 km to 1600 km in the experimental demonstration. This is the first application, to our knowledge, of a liquid crystal infiltrated photonic bandgap fiber in an optical transmission system and it demonstrates the OSNR improvement resulting from the use of the filter. Further experiments will demonstrate the benefits in a system with data modulated channels.

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