Wavelength-Division-Multiplexed Distributed Fiber Raman Amplifier Bus Network for Sensors

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ABSTRACT

We experimentally demonstrate a novel application of distributed fibre Raman amplification to a bus network for the wavelength multiplexing of optical sensors. Each sensor is uniquely identified by reflection from a fibre Bragg grating (FBG) and the distributed gain allows the number of sensors to be increased without using costly remote amplifiers. We show how the topology allows the received powers from the sensors to be equalised, even though only one Raman pump wavelength is used and we investigate how the performance depends on the launched pump power. The spectral filtering of the FBGs, combined with the distributed gain, jointly reduce the noise and we report measured signal to noise ratios.

Keywords: Wavelength-division multiplexing (WDM), data buses, distributed amplification, fiber Raman amplifier, optical fiber sensors.

1. INTRODUCTION

The multiplexing of large arrays of optical sensors has many diverse applications, such as monitoring the structural integrity, physical security and performance of remotely located equipment and buildings. Efficient schemes to multiplex the sensors allow fibre cabling and terminal components to be shared and therefore costs to be reduced. Bus architectures are widely used, mainly due to their simple cabling requirements[1]. For example, a wavelength-division-multiplexed (WDM) optical fiber-based network configured as a linear bus has been applied as a means of addressing and subsequently gathering data from optical sensors[2]. The all-fiber bus consists of a spine section that connects a series array of directional couplers leading to the sensing elements, followed by fiber Bragg gratings (FBGs). The sensors provide amplitude, phase, or polarisation modulation in response to the chosen environmental influence, while the gratings reflect incident signals within a narrow linewidth of predetermined centre wavelength and therefore uniquely identify the sensors being addressed.

Despite their appealing simplicity, fibre bus networks suffer from the disadvantage that the optical power at the sensors is in a descending geometrical sequence along the bus and it limits the number of sensors that can be addressed at acceptable signal-to-noise ratios (SNRs). Optical amplifiers (such as erbium doped fibre amplifiers, EDFAs) can be judiciously located within the bus to overcome this constraint but they are costly devices that require electrical power supplies. Alternatively, one can fabricate the bus entirely from erbium doped fibre with a low doping density to provide distributed gain[2, 3]. The strategy is successful but it requires special (and potentially expensive) fibre. In this paper we demonstrate the use of Raman amplification in the spine section of the bus to maintain the received powers from the sensors within acceptable bounds. Recently, dual-wavelength pumped Raman amplification, together with an EDFA, has been applied in a long-distance sensing system using a fiber Bragg grating[4, 5]. In our work we show how Raman gain can be used by itself to provide equalised received powers from a number of independent sensors.

2. NETWORK CONFIGURATION

Figure 1 shows the experimental configuration of the Raman-amplified bus. We constructed a four-port network but this number is by no means a performance limit. Each sensor incorporates a narrow-bandwidth FBG at a unique wavelength. The launched signals are ultimately incident on all of the sensors but the gratings ensure that each

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sensor returns only its characteristic channel towards the launching point (the head end) after passing through the sensor a second time. In our demonstration, the sensors were removed in order to make the power measurements independent of the particular measurands and so ensure greater generality of the results. Therefore, the network is not designed to be specific to any particular type of sensor. The Raman pump, signal(s) and receivers are co-located in one head end. Our demonstration was in a laboratory but in field operation, this strategy would remove the logistical inconvenience of electrical power feeds to remote locations. The Raman pump propagated co-directionally with the launched signal but contra-directionally with the returned signals from the gratings. Pumping from the opposite end of the bus (or even bi-directional pumping) is also possible. However, there is a general principle when cascading amplifiers that the lowest overall noise is achieved by placing the best amplifier at the start of the network[6] and this is the case in the configuration shown in Fig. 1. We used standard single mode (ITU-G.652 compliant) fibre throughout. Although it has a relatively low Raman efficiency (due to its large effective area), it is widely deployed in telecommunications networks, low cost and relatively free from impairments such as nonlinear cross-talk and Rayleigh back-scatter.

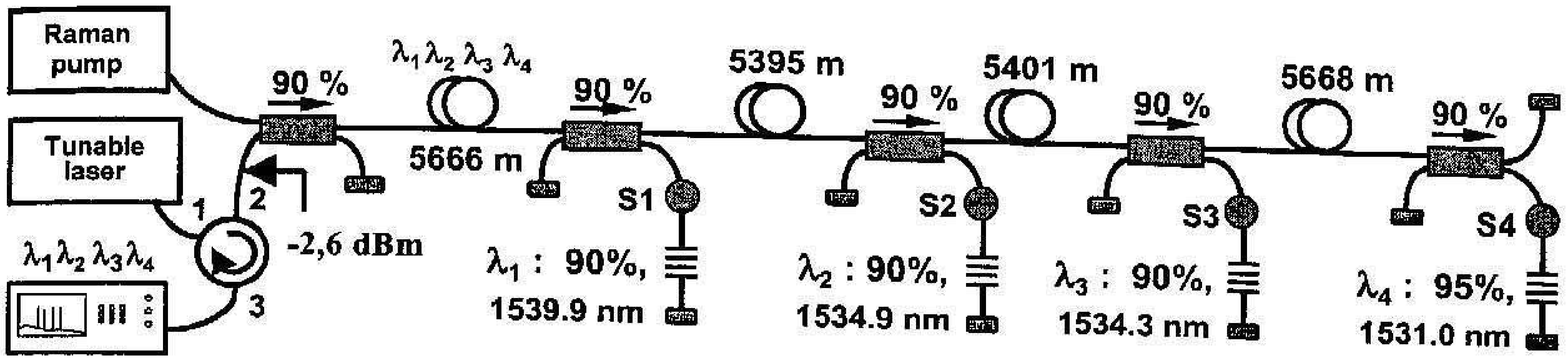

Fig.1. Wavelength-division-multiplexed distributed fiber Raman amplifier bus network. The fibre lengths and the grating peak wavelengths and reflectivities are indicated. Taking into account the circulator loss, the launched signal power at port 2 is –2.6 dBm.

The couplers shown in Fig. 1 were all similar, having ratios of 90:10 at the pump and all signal wavelengths. We used ~5 km fibre spans between the couplers to emulate a network of metropolitan-access dimensions (see Fig. 1 for precise values). However, there is no strict constraint on the lengths. (Indeed, greater spans would enable improved pumping efficiency.) All of the free terminations on the bus were refractive-index-matched to frustrate unwanted reflections. This is of particular importance to minimise multi-path interference[7]. The Raman pump laser was at 1445 nm and it could deliver up to 2 W power into the fibre prior to the launch coupler. The signal was provided by a tunable laser (1460 - 1580 nm) and after passing through the launch circulator, it had a power of –2.6 dBm and a spectral linewidth of 5 MHz. The launched pump was polarisation scrambled but there was a small residual elliptical polarisation of the signal laser. By taking multiple measurements, we estimate that this led to +/- 0.5 dB errors in the gain values.

The peak wavelengths and reflectivities of the gratings are marked on Fig. 1. They had a wavelength variation with temperature of 0.01 ^{o}C / nm. The grating wavelengths corresponded to frequency shifts from the pump ranging between 11.7 and 12.8 THz. These values were selected so as to be on the short wavelength side of the peak of the Raman gain profile (which is ~13.2 THz from the pump in the germano-silicate glass of standard single mode fibre). By making such a choice, the Raman gain profile increases with frequency shift. We used this property to obtain a degree of power equalization of the returned signals from the sensors. The strategy was to place the gratings corresponding to high Raman gains closest to the pump because that is where the signals experience the shortest interaction lengths. Conversely, gratings with relatively low Raman gain wavelengths were located further from the head end.

3. RESULTS

We start by considering an un-pumped network. The losses experienced by signals that are transmitted from the laser and returned to the detector are $10\mathrm{Log}_{10}\,[P_{\mathrm{returned}} / P_{\mathrm{launched}}]$. Assuming wavelength-independent couplers, a fibre loss of 0.2 dB/km at all signal wavelengths, the sensors' losses are at S1: 43.9, at S2: 47.7, S3: 51.6 and at S4: 55.6 dB. These values are dominated by a common component of 40 dB for making double passes through (a) the launch coupler and (b) the taping coupler at the target sensor. Figure 2 shows the four returned signals produced by tuning the signal laser consecutively to the grating wavelengths and it can be seen that their values differ because the couplers coupling ratio are not exactly 10 dB. The noise floor is dominated by the characteristics of the optical spectrum analyser (HP70951B).

In order to evaluate an amplifying network, we define a bus spine transparency power. This is the value of the Raman pump power that is sufficient to overcome the signal attenuation due to (a) the fibre and (b) discrete losses experienced at the couplers in passing from one amplifying span to the next. However, this power does not include compensation for the 2 x 10 dB losses in passing from the spine of the bus to the sensors and back again or for the losses of the launch coupler and circulator. Figure 3 was obtained with the Raman pump switched on. The power at 1445 nm was 500 mW because this is the bus spine transparency power for the return path to S4. All other conditions remain as in Fig. 2. It can be seen that the channel powers are increased and they sit on a pedestal of amplified spontaneous scattering (ASS). The out-of band ASS is purely backward propagating with respect to the pump because the gratings filter out the forward component. There is a degree of equalization of the received powers from the four gratings. This is possible as a result of the positioning of the wavelengths, as explained in Section 2. In this way the material Raman gain of the germano-silicate glass is highest when the pump-signal interaction length is shortest and least when the interaction length is longest.

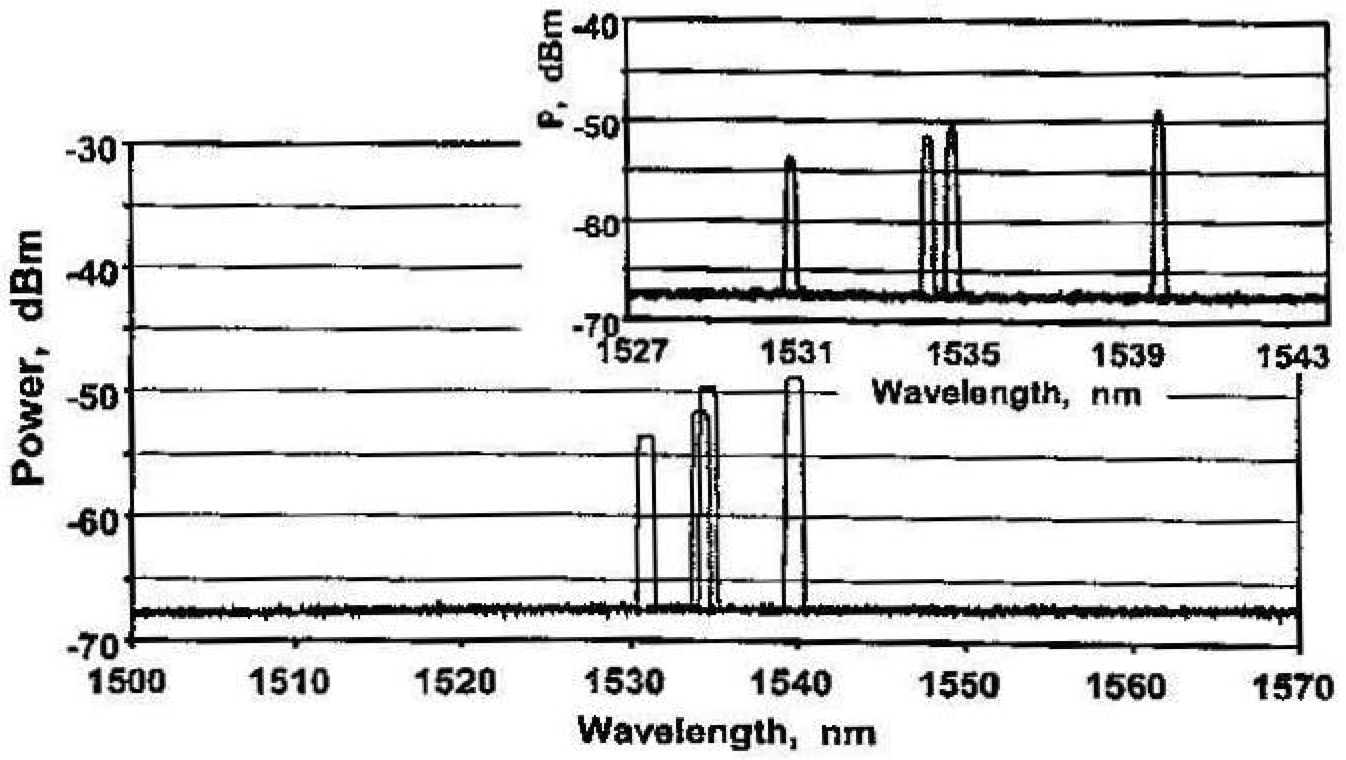

Fig. 2. Output power obtained without pumping the network. The insert shows expanded detail of the received signals.

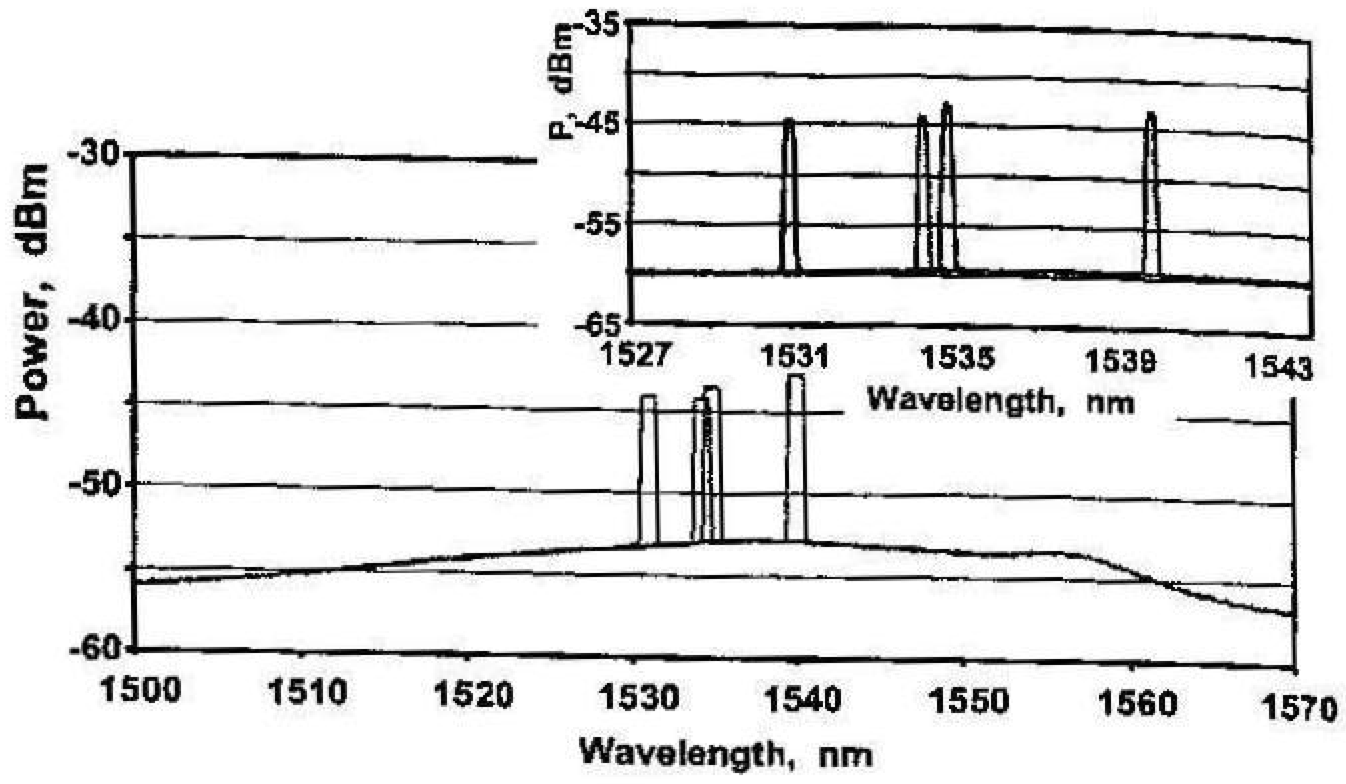

Fig. 3. Amplified output power obtained with an applied pump power of 500 mW. The signal wavelengths are the same as in Fig. 2. The insert shows expanded detail.

Table 1 presents the peak received powers and optical signal to noise ratios (OSNR) with and without pumping. It details the improved equalization of the channel powers. We believe that there would be scope to obtain yet better equalization if FBGs corresponding to a wider range of signal wavelengths were selected. Table 1 also indicates how the OSNR is reduced in three out of the four channels as a result of Raman amplification. We believe the OSNR values in the Raman amplified bus can be improved by optimizing the pumping strategy. Alternatively, other amplified bus designs that considerably improve the OSNR have been demonstrated [8, 9].

	S1 (1539.9 nm)	S2 (1534.9 nm)	S3 (1534.3 nm)	S4 (1531.0 nm)
$P_{received}$ (un-pumped), dBm	-48.8	-50.4	-51.4	-53.6
$P_{received}$ (pumped), dBm	-41.4	-40.9	-42.2	-42.6
OSNR (un-pumped), dB	18.8	17.1	16.1	13.9
OSNR (pumped), dB	16.3	16.6	15.4	15.3

Table 1 Summary of the received optical powers and optical signal to noise ratios, as presented in Figs.2 & 3.

Figure 4 is a plot of the variation of on-off Raman gain from the four sensors as a function of launched pump power. It shows straight line characteristics. As with the other measurements, it was performed with a single tunable laser that was consecutively adjusted to the four grating wavelengths. In such circumstances, one would expect the linear behavior that is characteristic of small signal gain. The bus spine transparency power value of 500 mW that was used previously is marked. Clearly, greater launched pump powers can provide greater gain to enable longer bus networks. When larger numbers of sensors are used, the total signal powers could induce gain saturation. However, it should be noted that we used higher launched signal powers than necessary for many applications and so we feel optimistic that one could avoid heavily saturated operation with appropriate reductions in the signal powers.

The network that we used in this demonstration had non-optimal couplers because they exhibited throughput losses of 0.45 dB at the pump wavelength. Further improvements could come from (a) better selection of grating wavelengths to increase the equalization of the return powers from the sensors and (b) alternative pump schemes, such as bidirectional pumping and/or multi-wavelength pumping to tailor the tilt of the gain profile. Moreover, the launch cupler wasted pump and signal power. Nevertheless, the results shown in Figs. 2-4 illustrate that Raman amplification has the potential to extend the number of sensors that can be multiplexed on a bus network.

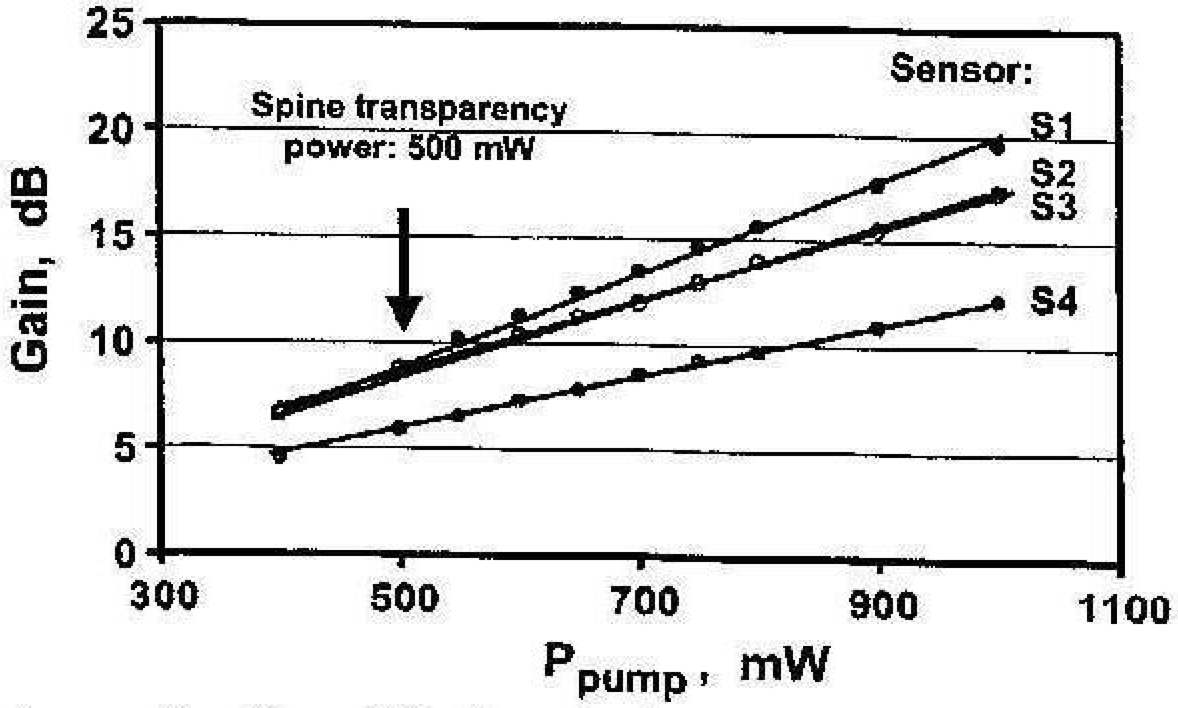

Fig. 4 Variation of on-off Raman gain as a function of the launched pump power. See Fig. 1 for the positions of the four sensors.

4. CONCLUSIONS

We have demonstrated a novel usage of distributed Raman amplification in a wavelength division multiplexed bus network for optical sensors in which the sensors are identified by fibre Bragg gratings. The gain provided is sufficient to overcome the throughput losses of the transmission fibre and the directional couplers, as well as partially equalizing the received powers from all of the channels, even though there is only one Raman pump wavelength. Our results obtained with high power pumping indicate that there is potential to extend the bus network to serve greater numbers of sensors.

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