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Going beyond limits in Brillouin distributed fibre sensors: challenges and possible approaches

(Invited Paper)

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***Abstract*—Brillouin distributed optical fibre sensing has been a subject of intense research and industrial development for more than twenty years, demonstrating its capabilities to be an effective and powerful measurement tool for a wide range of applications. Making use of sophisticated implementations, remarkable progresses on the sensing performance have been reported in the last decade, allowing significant improvements in spatial resolution and sensing range. However, the demand for distributed sensors with more performing features is steadily growing, imposing new and more challenging requirements to the sensor design. This paper presents a brief overview of the fundamentals of Brillouin distributed fibre sensing and reviews the main current limitations and challenges faced when the sensing capabilities are pushed beyond the state-of-the-art. Different possible approaches and methods to enhance and compare the sensing performance are also discussed.**

***Index Terms*—Optical fibre sensors; distributed fibre sensors; stimulated Brillouin scattering; nonlinear fibre optics.**

I. Introduction

The use of stimulated Brillouin scattering (SBS) to perform distributed measurements along an optical fibre was originally proposed as an alternative method to the standard Rayleigh-based optical time-domain reflectometry (OTDR) for the characterisation of the fibre attenuation [1]. However, the strain and temperature dependence of the acoustic wave velocity in the fibre makes SBS a more interesting method for distributed sensing [2]. Since its first implementation in the late 80's, the performance of Brillouin sensors has been steadily being improved over more than two decades. Nowadays, the critical factors limiting the performance of these systems have been clearly identified [3], [4], and intense research activities are ongoing in order to overcome some of the fundamental limitations and push the performance of Brillouin sensing beyond the state-of-the-art.

On the one hand, long-range Brillouin sensors (employing typically a spatial resolution in the metre scale) are essentially limited by the fibre attenuation, which gives a sensor response that decays exponentially with distance [3], and by the onset of nonlinear effects [5], [6], which limit the maximum pump and probe power that can be launched into the fibre. These factors seriously limit the signal-to-noise ratio (SNR) of the measurements [3], [4], especially near the farthest end of the fibre when long sensing distances are aimed at. Techniques that can provide considerable improvement in the SNR, enabling even more than 100 km range, are mostly based on optical pulse coding [7]–[9], distributed Raman amplification [10]–[12], or any combination of them [13]–[15].

On the other hand, the response time of the acoustic wave generated by SBS imposes serious limitations to the best spatial resolution that a conventional sensor scheme can reach. Since the response time of the acoustic wave is of the order of 10 ns, the ultimate spatial resolution is 1 m. Using pulses shorter than 10 ns in a standard BOTDA scheme leads to a significant spectral broadening and an intolerable reduction of the Brillouin interaction strength. Thus, in order to improve the spatial resolution of Brillouin sensors down to the centimetre or millimetre range actually requires very sophisticated methods. Some of the techniques that provide sub-metre resolutions in standard fibres are based on differential pulses [16], [17], correlation-domain [18], [19], and frequency-domain [20], among others. These methods allow for sub-metre resolutions; however they generally operate within a limited sensing range. Providing sub-metre resolution along many tens to kilometres is actually extremely challenging and only a few works have been reported in the literature so far.

II. Evaluation the performance of BOTDA sensors

A. Principle and sensor response

BOTDA sensors make use of the SBS process generated by a pump-probe technique [1], [2], in which a high-power pulsed pump interacts at each location along the fibre with a weak counter-propagating continuous-wave probe signal. The Brillouin gain (or loss) experienced by the probe, as a results of the interaction, can be acquired in the time domain for different pump-probe frequency offsets. The measurement procedure enables the reconstruction of a 3D map of the Brillouin gain (loss) spectrum as a function of the fibre location, as illustrated in Fig. 1. Spectral shifts in the measured local Brillouin spectrum (as depicted in the figure) give information about the local temperature and/or strain variations [2], so that a distributed profile of the fibre temperature or deformation (strain) can be obtained along the entire sensing length, with a spatial resolution given by the pump pulse width [2].

The sensor response, corresponding to the signal amplitude of the acquired time-domain traces $\Delta P_s^0(z)$, at each pump-

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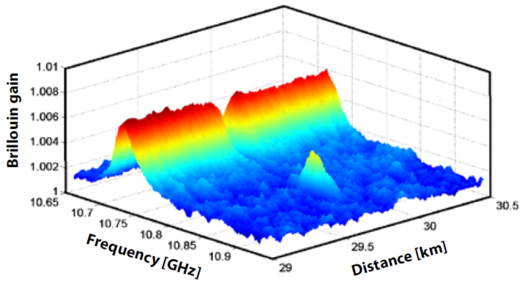

Fig. 1: 3D map of the Brillouin gain spectrum measured by a Brillouin sensor as a function of the fibre position. Temperature and/or strain variations are clearly observed as frequency shifts in the measured spectrum

probe frequency offset Δv can be written as [3]:

$$\Delta P_s^0(z) = \frac{g_B(\Delta v, z)}{A_{eff}} P_{si} \exp(-\alpha L) P_{pi} \exp(\alpha z) \Delta z \quad (1)$$

where $g_B(\Delta v, z)$ is the local Brillouin gain coefficient, A_{eff} is the fibre effective area, P_{si} and P_{pi} are the probe and pump power launched into the fibre, α is the fibre loss coefficient, L is the fibre length, and Δz is the spatial resolution.

Considering that in the vast majority of situations the noise of the time-domain traces is constant [4], the SNR is expected to decay exponentially in direct proportion to the sensor response described in Eq. (1) [3], [4]. However, it is also important to notice that the amplitude contrast of the measured traces, and the corresponding SNR, do not only depend on the exponentially-decaying local pump power, but also on the total losses experienced by the probe signal, thus doubling the effects of the fibre attenuation [3]. For this reason the performance of the sensor must be always evaluated at the farthest fibre end, where the lowest SNR takes place.

B. Relation between SNR and measurand resolution

Note that in Brillouin distributed optical fibre sensing the local temperature and strain information is retrieved by estimating the local peak gain frequency using a fitting procedure [3]. Therefore, the measurand (temperature or strain) resolution is essentially given by the uncertainty on the Brillouin frequency estimation, which in turn strongly depends on the noise level of the measurements and the number of spectral points used in the fitting. A simple expression for the frequency uncertainty $\sigma_v(z)$ as a function of the SNR, the frequency scan step (δ) and the full-width at half-maximum Brillouin spectral width (Δv_B) can be written as [3]:

$$\sigma_v(z) = \frac{1}{SNR(z)} \sqrt{\frac{3}{4} \delta \cdot \Delta v_B} \quad (2)$$

where $SNR(z)$ is the signal-to-noise ratio along the temporal BOTDA trace measured at the peak gain frequency. Eq. (2) points out that the SNR is the ultimate parameter affecting the performance of a Brillouin distributed optical fibre sensor, and therefore, any effort to improve the sensing performance should provide a significant enhancement in the SNR.

C. Figure-of-merit in BOTDA sensors

The well-known trade-off between spatial resolution, sensing range and measurand resolution (proportional to σ_v) is evident from Eqs. (1)-(2). All these parameters, defining the performance of a sensor, are actually interrelated through the sensor response and SNR on the traces [3], [4]. Since spatial resolutions, sensing ranges and measurement times (given by the number of averaged traces) can be freely and independently chosen, the comparative evaluation of the performance of BOTDA systems is not straightforward. For instance, how do we really compare a 50 km-long sensor offering 2 m spatial resolution and 1.5 MHz frequency uncertainty with a 25 km-long sensor offering 1 m spatial resolution and 1 MHz uncertainty? As an answer to this question, the following figure-of-merit (FoM) has been recently proposed to fairly compare, with an objective metric, the performance of Brillouin distributed sensors [3]:

$$FoM = \frac{(\alpha L_{eff}^2 exp\{(2 + f_1)\alpha L\}}{\Delta z \sqrt{N_{Tr} \cdot N_{Av}} \sqrt{\frac{\delta \cdot \Delta v_B}{\sigma_v}}} \quad (3)$$

where f_1 is a parameter that takes into account the fibre configuration, N_{Tr} is the number of *different* traces required at each scanned frequency (e.g. $N_{Tr} = 1$ for the standard scheme, $N_{Tr} = 2$ in a differential pulse scheme), and N_{Av} is the number of averaged traces. This FoM has been simply defined to be propostional to the SNR, including some considerations based on the limitations imposed by pump depletion [6] and nonlinear effects [5]. Eq. (3) points out that extending the range of a BOTDA sensor is actually much more challenging than improving the spatial resolution. This is because SNR exponentially decays with distance, whilst the spatial resolution only has a linear impact [3], [4].

III. Techniques to Extend the Measurement Distance in Long-Range BOTDA Sensing

A. Limitations to sensing performance

As previously mentioned, the fibre attenuation is the factor that imposes the most stringent limitation to the performance of Brillouin sensors, especially for long ranges. A common strategy to extend the sensing range of a conventional scheme is to use long spatial resolutions; however, this generally leads to similar figure-of-merits, providing no real improvement to the sensor performance. An alternative could be to increase the peak power of the pump pulses; however, this quickly leads to pump depletion issues [6] and nonlinear effects [5], such as modulation instability and amplified forward spontaneous Raman scattering, which reduce drastically the maximum sensing distance, as illustrated in Fig. 2.

In order to obtain a real increment in the FoM of BOTDA sensors, dedicated advanced techniques have to be used. It has been demonstrated that there are essentially two methods providing significant improvement in the SNR of long-range BOTDA sensors; these are: optical pulse coding [7]–[9] and distributed Raman amplification [10]–[12]. An interesting aspect is that both methods can be combined [13]–[15], so that,

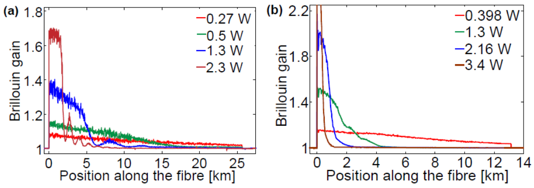

Fig. 2: Limitations imposed by (a) modulation instability and (b) amplified forward spontaneous Raman scattering, in long-range Brillouin distributed optical fibre sensing. Both nonlinear effects deplete the pump power imposing severe limitations to the maximum sensing range

after a smart and dedicated optimisation, very long sensing ranges can be reached, as it will be shown later in this section.

B. Optical pulse coding

Optical pulse coding uses sequences of short pulses (see Fig. 3) that are launched into the sensing fibre in bursts at a low repetition rate [7], [8], as in a conventional single-pulse scheme. This way a higher average pump power is launched into the fibre, while the peak pulse power can remain below the threshold of detrimental nonlinear effects. Measured time-domain traces contain the linear superposition of the (delayed) sensor response for each of the pulses in the sequence. Therefore, to retrieve the single-pulse fibre response, a suitable decoding method is required [7], [8], based on a linear transformation of the measured coded traces. This process improves the SNR of the decoded time-domain traces in comparison to the standard single-pulse case, under the same measurement conditions [7]–[9]; i.e. considering the same number of averaged traces, and hence, same acquisition time.

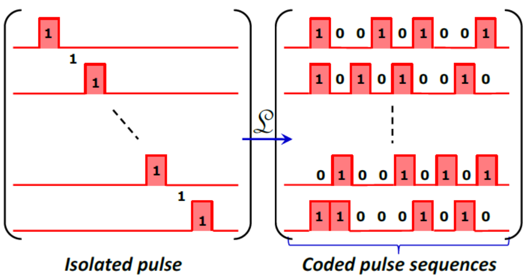

Fig. 3: Principle of optical pulse coding. Several code sequences are generated by a linear transformation of delayed copies of a single pulse. The total energy of the sequence is much higher than the one of the single pulse, while the peak power remains the same and below the onset of nonlinear effects

According to the state-of-the art, coding methods for Brillouin sensing enhancement can essentially be divided into 3 categories: *i)* conventional unipolar codes (i.e. sequences of 0's and 1's), such as Simplex [7], [8] and Golay codes [9], *ii)* time-frequency codes [21] (so-called coloured codes), based on for instance pseudo-random pulse sequences or on a modified version of Simplex codes, and *iii)* bipolar codes (i.e. sequences of -1's and 1's), such as bipolar Golay codes [22], which sequentially combine Brillouin gain and loss processes. The SNR enhancement provided by such methods is quantified by the coding gain. For optimal unipolar codes, such as Golay and Simplex codes, the coding gain is essentially the same (for sequences $>$ 63 bits), being equal to $\sqrt{L_c}/2$, where L_c is the code length [7], [8]. Fig. 4 shows a 10.3 dB SNR enhancement, obtained with a 511 bit Simplex coded BOTDA system, using 1 m spatial resolution over a 50 km range. The figure shows a substantial noise reduction when coding is used, which can be helpful to extend the sensing range, improve the spatial or measurand resolution and/or to reduce the measurement time.

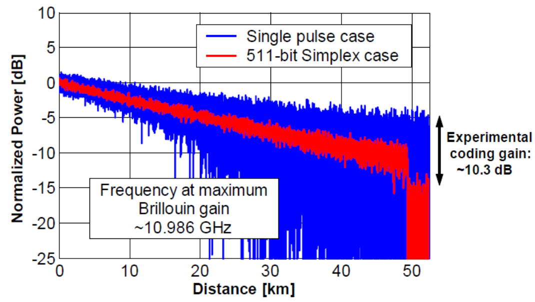

Fig. 4: Temporal BOTDA trace, measured with 511-bit Simplex codes (red curve) and the conventional single-pulse (blue curve). Both traces are acquired with the same measurement time, corresponding to 2k averaged traces

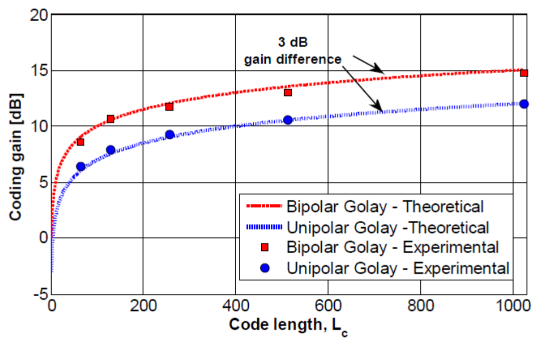

Fig. 5: Coding gain of unipolar (blue curve and dots) and bipolar (red curve and dots) Golay codes for different code lengths L_c

Considering the most-advanced coding methods [21,22], time-frequency codes and bipolar Golay codes offer an improved coding gain of $\sqrt{L_c/2}$ and L_c, respectively, i.e. 1.5 dB and 3 dB higher than the conventional coding methods for the same sequence length L_c. This becomes evident in Fig. 5, which compares the coding gain of unipolar and bipolar Golay codes obtained under similar experimental conditions.

An important aspect to take into account is that all coding methods applied to Brillouin sensing must be implemented using pulses with return-to-zero (RZ) format [23]. This format is actually essential to avoid detrimental effects resulting from the non-instantaneous decay of the acoustic wave, which leads to an undesired nonlinear Brillouin interaction that breaks the linearity required by pulse coding techniques [23]. If pulses with non-RZ are used, sequences containing a large number of consecutive 1's will induce a larger Brillouin gain than those having 1's evenly distributed in the sequence. This effect results in severe trace distortions, potentially leading to significant measurement errors. On the other hand, RZ pulses (with pulse separation greater than 50 ns) allow the acoustic field to vanish enough before next pulses in the sequence re-activate the acoustic wave [23]. This ensures linear Brillouin amplification and avoids trace distortions due to the decoding.

C. Distributed Raman amplification

Distributed Raman amplification is another method that enables significant improvement in the performance of long-range Brillouin sensors [10]–[12]. In this case stimulated Raman scattering provides distributed optical amplification to pump and probe signals, enhancing the Brillouin interaction, so that the SNR on the measured traces results significantly increased. The technique allows different possible configurations, using forward, backward or bi-directional Raman pumping, with first, second and eventually higher order schemes.

A dedicated optimisation of the method is required to avoid that the maximum pump and probe powers (which are reached after some km along the fibre) do not exceed the threshold levels of nonlinear effects [12]. Fig. 6 shows a typical temporal BOTDA trace obtained with a first-order bidirectional Raman-assistance along a 120 km-long fibre. The figure points out that the minimum amplitude of the trace does not occur at the end of the fibre, as in the conventional scheme, but a few kilometres before the end, which represents the fibre location with the lowest SNR and where the worst measurand resolution is positioned over the entire fibre length [11], [12].

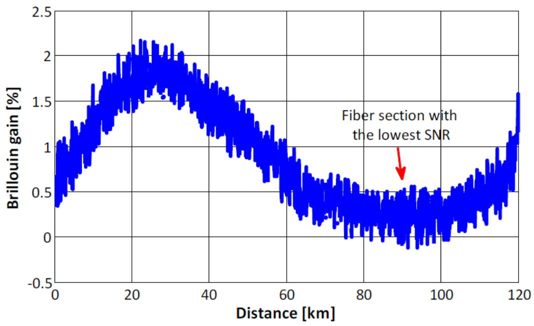

Fig. 6: Temporal trace in a BOTDA sensor assisted by bi-directional first-order Raman distributed optical amplification. The maximum and minimum amplitudes take place at 25 km from the near and far fibre ends, respectively

One of the main limitations of the Raman-assistance method is the relative intensity noise (RIN) that is transferred from the backward Raman pump to the probe signal (both co-propagating in backward direction from the far fibre end). However, in order to mitigate the effects of RIN transfer, 3 methods have been proposed: *i)* use of low-RIN Raman pumps, such as semiconductor lasers [12], *ii)* use of balanced detection [24], and *iii)* the use of a vector-BOTDA system based on heterodyne detection [25].

D. Ultra-long range BOTDA sensor over a 240 km-long fibre loop configuration

Combining optical pulse coding and Raman assistance more than 120 km have been reported, with spatial resolution of 1-5 m [13], [14]. However, since pump and probe signals must counter-propagate in the optical fibre, the real remoteness of BOTDA sensors is in practice restricted to half the fibre length, imposing serious constrains for some applications.

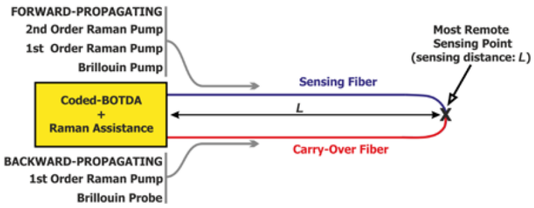

Fig. 7: Linear fibre configuration used to extend the sensing range of BOTDA sensors. Half of the fibre is used as a sensing element, while the other half is used to convey the probe signal up to the most remote end of the sensing fibre

A suitable scheme to increase the remoteness of a BOTDA sensor is shown in Fig. 7 [15], in which the length of the optical fibre connected to the system is doubled, so that only half of it is used for sensing purpose (referred as sensing fibre), while the other half is required to propagate the probe signal up to the most remote point in the sensing fibre (referred as carry-over fibre) [15]. However, it is important to mention that this implementation is not straightforward due to the additional losses that the probe wave experiences as a consequence of the extended fibre length. For instance, extending the remoteness of a standard 120 km-long BOTDA sensor (i.e. limited to monitor events up to 60 km away from the interrogating unit) up to 120 km requires a total fibre length of 240 km, placed in the configuration shown in Fig. 7. This implies that the probe signal has to experience an additional power attenuation of 24 dB, which have to be recovered to provide reliable sensing.

After optimising pump and probe powers as well as the Raman pump power launched into the fibre, distributed temperature measurements have been possible up to a remote point located at 120 km far from the interrogating unit [15], using a 240 km-long single-mode fibre and 5 m spatial resolution, as shown in Fig. 8. This figure shows the capability of the sensor to detect temperature/strain variations at a real distance of 120 km, corresponding to the farthest remoteness achieved by a BOTDA system [15]. This has been possible only due to the high SNR enhancement provided by the optimised combination of bidirectional seeded second-order Raman-assistance and 255 bit Simplex coding.

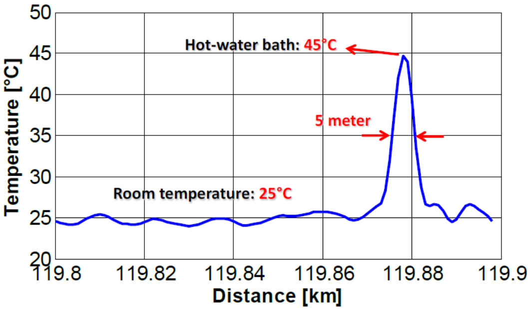

Fig. 8: Hot-spot detection at 120 km away from the sensing unit, obtained in a BOTDA sensor combining seeded second-order Raman-assistance and 511-bit Simplex coding, and using a 240 km-long fibre loop configuration, 5 m spatial resolution and 2k time-averaged traces

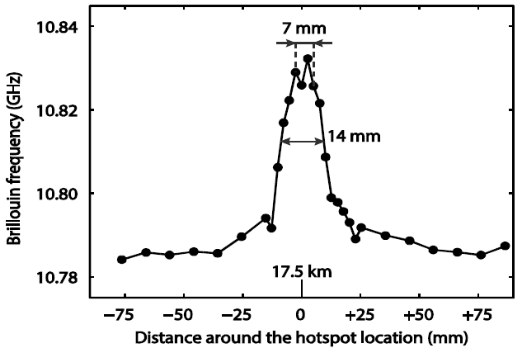

Fig. 9: 14-mm hot-spot detection at 17.5 km distance using a phase-correlation method, demonstrating more than 1'000'000 resolved points along the fibre

IV. Extending the Sensing Range of Sub-Metre Resolution Brillouin Sensors

Another interesting field of research is related to the sensing range extension of schemes for sub-metre resolution. These kinds of schemes are usually limited in their maximum range, especially when the spatial resolution is improved down to a few centimetres (<10 cm) or even to a millimetre level. In addition to the need of pre-activating the acoustic wave [16]–[19], the main limitation to the sensor performance in schemes for sub-metre resolution is the short Brillouin interaction taking place in the fibre, which leads to a very small sensor response, as described in Eq. (1) (note that this expression is also valid for sub-metre schemes, provided that the acoustic wave is pre-activated [3], [4]). This means that the Brillouin interaction in a system offering, for instance, a 10 cm resolution is expected to be 10 times lower than in a system designed for 1 m spatial resolution; thus leading to a SNR reduction of 10 dB, which imposes considerable limitations to the sensing range [3]. However, these schemes generally benefit from the possibility of using very high pump and probe powers due to the increased power threshold for nonlinear effects along short fibre lengths. This has allowed optimised schemes to perform distributed sensing with a large number of resolved points. For instance, differential pulse methods, such as differential pulse-width pair method (DPP-BOTDA) and Brillouin echoes (BEDS) have respectively reported sensing ranges of 2 km and 5 km, for spatial resolutions of 2 cm and 5 cm in each case [16], [17]; providing up to 100'000 resolved points with a single system. Combining DPP-BOTDA with Raman-assistance and optical pulse coding, a sensing range of 60 km with a spatial resolution of 25 cm has been reported [26], representing a significant increase in the number of resolved points (up to 250'000).

Recently a novel scheme based on the phase-modulation of probe and pump signals has been proposed to confine the Brillouin interaction at given well-defined fibre locations [19], referred as *correlation peaks*. Some advantages of this phase-modulated correlation-domain method are: *i)* very high spatial resolution can be reached (a few cm or even mm), and *ii)* the technique can be simply combined with time-domain methods [27], [28], resulting in a significant performance enhancement. Although preliminary implementations have demonstrated the possibility to resolve up to 300'000 points [27], more recent modifications and optimisation of the system have increased the number of points by one order of magnitude, reaching a record of more than 1'000'000 resolved points with a single system [28]. Fig. 9 shows the detection of a 14 mm hot-spot at the end of a 17.5 km-long single-mode fibre, with a measurand resolution of 1.5°C and 1 k averages. This is to the longest range monitored with such a high spatial resolution [28].

V. Conclusion

In conclusion, improving the performance of distributed Brillouin sensors is undoubtedly a challenging task, which requires the implementation of innovative and smart solutions to overcome the fundamental limitations existing in the state-of-the-art. This paper has presented a general overview of the principle and main limitations in Brillouin sensing, reviewing also some advanced methods for performance enhancement. The SNR of the measurements has been found to be the most important parameter defining the performance of Brillouin sensors; and hence, novel advanced techniques should focus on enhancing the sensor response and the SNR. For an objective evaluation of the sensor performance, a figure-of-merit has been presented, which results in an essential tool to fairly compare the benefits brought by different techniques. Thus, while the FoM of commercial systems is generally in the order of 100 or below, advanced BOTDA schemes offer much higher FoM.

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