A Study of the Linearity Performance of a Stimulated Brillouin Scattering-Based Microwave Photonic Bandpass Filter

Mattia Pagani, Erwin H. W. Chan, and Robert A. Minasian, *Fellow, IEEE, Fellow, OSA*

***Abstract*—The linearity of stimulated Brillouin scattering (SBS) is studied in detail for the first time. A closed-form expression which measures the linearity of an SBS system is derived. This expression allows one to design the region of linear operation, and the amount of Brillouin gain of an SBS system, by altering some basic system parameters. The theory presented is experimentally verified using an SBS-based microwave photonic filter structure. The effect of the length of the Brillouin medium on the linearity of the filter is investigated, and a 9.7 dB extension in the dynamic range is demonstrated by reducing the length of the fibre used as the Brillouin medium, from 25 to 0.57 km, while the filter stopband rejection level remains 30 dB.**

***Index Terms*—Brillouin pump depletion, dynamic range, linearity, microwave photonics, photonic signal processing, stimulated Brillouin scattering.**

I. Introduction

PHOTONIC signal processing is attractive for processing high bandwidth signals [1]. It offers the ability to realise functions that are either very difficult to achieve or perhaps, not even possible in the RF domain: for instance, very high-resolution bandpass filtering that also has wide tunability. There have been several microwave photonic approaches reported to date, including many based on discrete time processor structures [2], however they have been limited by the inability to realise both a very high resolution response and a high free spectral range (FSR) simultaneously.

The use of stimulated Brillouin scattering (SBS) in optical fibre is a highly attractive approach for solving these problems to implement high-resolution microwave photonic filters without being subject to the FSR limitation of discrete-time structures. SBS can be used to obtain high Q-factor microwave photonic filters because of its inherent narrowband nature. Moreover, it features a low threshold power, and simple initiation. SBS is an inelastic nonlinear optical effect that takes place when the light launched into an optical fibre exceeds a certain threshold. It is manifested through the generation of a narrow-linewidth backward-scattered Stokes wave with a frequency offset from the pump laser given by the Brillouin frequency shift of the medium (around 11 GHz in standard silica fibre, at 1.55 μm).

Microwave photonic filters relying on SBS are capable of achieving a highly selective, single bandpass response at high frequencies [3], [4], with a passband width ranging from 20 to 50 MHz depending on the fibre used. They can also be tuned over wide frequency ranges, using relatively simple structures [5], [6].

While all these implementations present very attractive characteristics, none of them have addressed the issue of linearity, which can be very important in the SBS process. What is meant here is that the dynamic range, or the range over which the SBS-based filter operates in a linear manner, can be substantially restricted. When this occurs, the output RF power of the filter is no longer directly proportional to the input RF power. This effect has been almost completely ignored to date in the literature, except for Yao [7], who took note of it, but did not study it in detail.

A signal processor is termed linear if it displays the homogeneity and additivity properties. This implies that the transfer function of a linear system is independent of the input signal. In contrast, a nonlinear signal processor may exhibit a particular frequency response when the input RF signal is a small signal, but when the input RF signal power increases, the frequency response of the nonlinear processor may be changed. It is clear that in practice, one does not have absolute control over the power, or the frequency content, of the input RF signal into a processor, for this it is essential that the frequency response of the signal processor be predictable and independent of the input RF signal. Signal processors need to be linear, i.e. to have an input-independent transfer function, in order for them to be operated in practice.

In this paper, we present the first investigation of the linearity of an SBS-based microwave photonic filter. We analyse the response of an SBS-based filter for different values of input RF power, and describe the requirements that must be met in order to achieve linear operation. These requirements are derived theoretically for a basic SBS-based filter. Experimental results are presented that demonstrate a significant increase in the linear range of operation for a basic SBS-based filter, by means of a technique based on reducing the length of the fibre used as the Brillouin medium.

II. Theory

SBS in optical fibres occurs when the power of the light launched into the fibre exceeds a certain threshold. Once this

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The authors are with the School of Electrical and Information Engineering, Fibre-optics and Photonics Laboratory, University of Sydney, Sydney, N.S.W. 2006, Australia (e-mail: mattia.pagani@sydney.edu.au; erwin.chan@sydney.edu.au; robert.minasian@sydney.edu.au).

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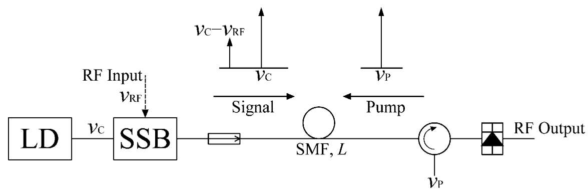

Fig. 1. Fundamental structure of SBS-based microwave photonic filter.

occurs, an acoustic wave will be generated inside the fibre, through electrostriction [8]. In practice, SBS can also be initiated by counterpropagating two optical waves. Usually, the wave with the higher power is known as the pump. The other wave is known as the seed wave. In general, both waves travel in opposite directions within the same fibre without affecting each other. However, when the frequency of the seed wave matches the Stokes frequency, namely the pump frequency downshifted by the Brillouin frequency shift, strong coupling will occur between the two waves. In this case, the interference between the pump and seed waves will serve to generate the acoustic wave from which SBS occurs. The scattering of the pump wave from this acoustic wave will act as a source that tends to increase the amplitude of the seed wave, which will in turn reinforce the pump-seed interference, and the amplitude of the acoustic field. This positive feedback mechanism effectively produces a narrow-linewidth gain and loss spectrum in the seed wave at frequencies equal to the difference and the sum of the pump frequency, and the Brillouin frequency shift, respectively. Effectively what happens is that the pump wave loses its energy and gives a part of it to the seed wave, allowing it to grow.

A structure that is representative of most microwave photonic filters based on SBS, and which also allows the study of the linearity performance, is shown in Fig. 1. An optical carrier, with frequency ν_c, undergoes single sideband (SSB) modulation by an RF signal. The RF-modulated optical signal is then counterpropagated with a continuous wave (CW) laser output called the pump, with frequency ν_p, in a length of optical fibre L. The spectra of the forward and counterpropagating waves are shown in Fig. 1. When the modulation sideband has a frequency in the vicinity of $\nu_p - \nu_B$, where ν_B is the Brillouin frequency shift, it is amplified substantially through the SBS process. This amplification only occurs over the very narrow frequency range corresponding to the Brillouin linewidth. The amplified sideband then beats with the carrier at the photodetector to produce a highly frequency-selective single-passband response. It should be noted that the Stokes wave in this case is just the modulation sideband which has a frequency in the vicinity of $\nu_p - \nu_B$. Optical waves at other frequencies, e.g. the carrier frequency, travelling along the Brillouin medium are not affected by the SBS process, since their frequency does not fall in the vicinity of $\nu_p - \nu_B$.

The linearity and dynamic range problem for the SBS-based microwave photonic filter can be understood with reference to Fig. 2. This shows the typical measured output RF power as a function of input RF power when the RF frequency is at the passband centre of the SBS-based microwave photonic filter, and when the fibre length is 25.32 km. It can be clearly seen

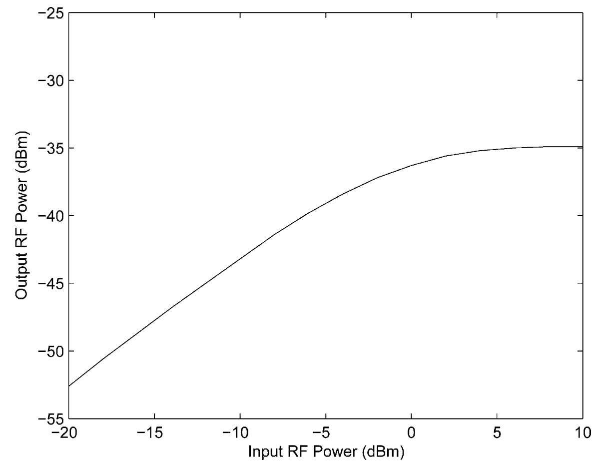

Fig. 2. Measured output RF power as a function of input RF power.

that the characteristic deviates from linearity at quite low power levels. This causes the dynamic range of operation to be restricted. Hence it is essential to find techniques to extend the dynamic range, in order to enable SBS-based filters to be usable in practice.

The steady state coupled differential equations, which describe the SBS process, are given by [9]

$$\frac{dP_p}{dz} = -\frac{g(\nu)}{A_{\mathrm{ao}}} P_p P_s - \alpha P_p \tag{1}$$

$$\frac{dP_s}{dz} = -\frac{g(\nu)}{A_{\mathrm{ao}}} P_p P_s + \alpha P_s \tag{2}$$

where P_p and P_s are the powers of the pump and Stokes waves respectively, α is the fibre loss coefficient (assumed to be the same for both the signal and pump waves), A_{ao} is the acousto-optic effective area, which is the area of the overlap between optical and acoustic modes inside the fibre, and $g(\nu)$ is the spectral profile of the Brillouin gain, which has Lorentzian shape and can be written as

$$g(\nu) = g_0 \frac{(\Gamma_B/2)^2}{(\nu_p - \nu_B - \nu)^2 + (\Gamma_B/2)^2} \tag{3}$$

where g_0 is the line centre gain factor (m/W), Γ_B is the Brillouin linewidth, ν_B is the Brillouin frequency shift, ν_p is the frequency of the pump wave, and ν is the frequency of the Stokes wave.

The system described by (1) and (2) occurs quite frequently in other natural processes, and has been studied extensively. However, one feature of SBS that makes these equations particularly challenging to solve are the boundary conditions. That is because, in order for coupling to occur between the Stokes and pump waves, they must be travelling in opposite directions. So while the pump is injected at one end of the fibre, $z = 0$, the Stokes wave is actually launched from the other end of the fibre, $z = L$, where L is the length of the fibre through which SBS is occurring. It is clear that the only two known boundary conditions are $P_p(0)$ and $P_s(L)$.

While it is true that SBS is an inherently nonlinear process, its behaviour is approximately linear provided that some conditions are satisfied, as first presented by Tang in [10]. Specifically, Tang showed that in the limit $P_s(0)/P_p(0) \to 0$, the SBS amplification process becomes linear. For this condition to be satisfied in practice, the intensity of the modulation sideband, which acts as the Stokes wave, must be small enough such that the pump wave is not significantly depleted via the SBS process as it travels through the fibre. Provided that Tang's condition is satisfied, one can write an approximation to (1)

$$\frac{dP_p}{dz} \approx -\alpha P_p. \tag{4}$$

Under this no-depletion approximation, it is possible to solve (2) and (4) to find an analytical expression for the Stokes power along the fibre

$$P_s(z,\nu) = P_s(L,\nu)e^{\alpha(z-L)}\exp\left[\frac{g(\nu)P_p(0)}{\alpha A_{\text{ao}}}\left(e^{-\alpha z} - e^{-\alpha L}\right)\right] \tag{5}$$

so that the output Stokes power, at the fibre end which corresponds to $z = 0$, is given by

$$P_s(0,\nu) = P_s(L,\nu)e^{-\alpha L}\exp\left(\frac{g(\nu)}{A_{\text{ao}}}P_p(0)L_{\text{eff}}\right) \tag{6}$$

where $L_{\text{eff}} = \frac{1}{\alpha}\left(1 - e^{-\alpha L}\right)$ is a parameter that describes the effective interaction length in the fibre. The derivation of (5) can be found in [8]. From (6), the magnitude gain $G(\nu)$ of the SBS process is defined as

$$G(\nu) = \frac{P_s(0,\nu)}{P_s(L,\nu)e^{-\alpha L}} = \exp\left(\frac{g(\nu)}{A_{\text{ao}}}P_p(0)L_{\text{eff}}\right). \tag{7}$$

The reason the SBS gain is not simply equal to $P_s(0,\nu)/P_s(L,\nu)$ is that the fibre used as a Brillouin medium has an intrinsic loss. This loss term, $e^{-\alpha L}$, is separate from the Brillouin gain. For example, in the absence of a pump wave, the power of the Stokes wave is reduced by the factor $e^{-\alpha L}$, as it traverses a fibre of length L. In the presence of a pump wave however, the Stokes wave experiences both fibre losses and Brillouin gain, by a factor $G(\nu)$.

III. Condition for Linearity

As stated in Section I, a signal processor is termed linear if its transfer function is independent of the power of the input signal. In a system that uses SBS amplification, the input signal is the Stokes wave. Equation (7) above expresses the frequency response of a signal processor based on SBS amplification. It is clear from (7) that this frequency response is independent of the input signal power $P_s(L,\nu)$ so that, at any given frequency ν, the gain experienced by the Stokes wave depends not on the Stokes power itself, but only on the pump power injected in the fibre. The power linearity expressed by (7) was derived under the assumption that the SBS pump wave is not depleted by the SBS process, expressed mathematically in (4). If this assumption does not hold in an actual operating condition, the SBS frequency response will no longer be described by (7), and it will become a function of the input signal, i.e. Stokes, power. Hence, the amplification provided by SBS is a linear process only under the condition that the pump wave is not depleted due to SBS.

This condition for linearity, often termed the undepleted pump approximation, has been vaguely studied in the literature, mainly in the field of optical amplifiers which make use of SBS [11]–[14]. The reasoning behind it is that if the Stokes power is low, the SBS process is not strong, and the pump wave does not deplete significantly. This might be taken to mean that the only way to achieve linear operation is to use a low Stokes power. However, this is a strong condition, which can be relaxed, provided that other requirements are met.

An analytical expression describing the conditions required for linearity can be obtained by studying the coupled equations (1) and (2). The general solution of (1) is

$$P_p(z) = P_p(0)\exp\left[-\int_0^z\left(\frac{g(\nu)}{A_{\text{ao}}}P_s(\zeta,\nu) + \alpha\right)d\zeta\right]. \tag{8}$$

If the pump power is not depleted due to SBS, then as the pump wave travels through the fibre, the only mechanism which reduces the pump power is the intrinsic fibre loss, meaning that the pump power $P_p(z)$, reaching the end of the fibre of length L, is equal to $P_p(0)e^{-\alpha L}$. This approximation, together with (8) can be used to obtain the condition required for the undepleted pump approximation to hold:

$$\frac{g(\nu)}{A_{\text{ao}}}\int_0^L P_s(\zeta,\nu)d\zeta \ll 1. \tag{9}$$

The integral in (9) can only be evaluated numerically, because there is no known analytic solution to the coupled equations (1) and (2). However, it is possible to go one step further. Assuming condition (9) is true, then a good approximation to $P_s(z)$ is given by (5). By examining (5), it is clear that $P_s(z)$ can grow to be quite large, thus contradicting the assumption that (9) is true. Therefore, while condition (9) implies (5), equation (5) does not imply (9).

For this, in the case that the Stokes power launched into the fibre is very small, a good approximation to $P_s(z)$ is given by (5). Provided that the approximation satisfies the condition given in (9), then the approximation can be taken as being accurate. If the approximation does not satisfy (9) then, by contradiction, the approximation is no longer accurate and SBS is not occurring linearly. By substituting (5) into (9),

$$\frac{g(\nu)}{A_{\text{ao}}}\int_0^L P_s(\zeta,\nu)d\zeta = \frac{P_s(L,\nu)}{P_p(0)}\frac{K}{\alpha}e^{-\alpha L}\exp\left(\frac{K}{\alpha}e^{-\alpha L}\right) \cdot \left[\frac{K}{\alpha}\left(\text{Ei}\left(\frac{K}{\alpha}\right) - \text{Ei}\left(\frac{K}{\alpha}e^{-\alpha L}\right)\right) - e^{\frac{K}{\alpha}}\right] \tag{10}$$

where

$$K = \frac{g(\nu)}{A_{\text{ao}}}P_p(0) \tag{11}$$

and

$$\text{Ei}(x) = \int_{-\infty}^x \frac{e^{-\zeta}}{\zeta}d\zeta \tag{12}$$

is a special function known as the exponential integral.

For a given SBS-based microwave photonic filter setup, the parameters which describe the operation of the filter are $P_p(0)$, α, L, $g(\nu)$, and A_{ao}. These parameters may be adjusted to

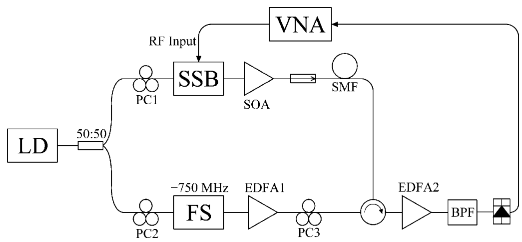

Fig. 3. Experimental setup of the SBS-based microwave photonic filter.

achieve a certain SBS gain, and they are the ones which can be controlled. The only unknown parameter of the filter is the power of the input information signal into the modulator, which determines the Stokes power $P_s(L)$. Since we want the filter to operate linearly over a large input RF power range, a more suggestive form for (9) would be

$$\Upsilon P_s(L,\nu) \ll 1 \tag{13}$$

where Υ is the expression which multiplies $P_s(L,\nu)$ in (10). For $K/\alpha > 50$, a good approximation to Υ is

$$\Upsilon \approx \frac{1}{P_p(0)}\left[G(\nu)e^{-\alpha L} - e^{\alpha L} - \frac{\ln G(\nu)}{1-e^{-\alpha L}}\right]. \tag{14}$$

Note that in (14) the SBS gain $G(\nu)$ and the injected pump power $P_p(0)$ are not independent, but they are in fact related through (7). The condition described by (13) bears some resemblance to that first derived by Tang [10], who said that, neglecting the medium losses, the SBS process is linear in the limit $P_s(0)/P_p(0) \to 0$.

The linearity parameter Υ serves as a measure of how linear an SBS system is. Since it is independent of the input Stokes power, it can be used to compare the linearity of different SBS systems. In order to maximise the linearity of an SBS-based microwave photonic filter, one should design the system so as to minimise Υ. By examining the expression for the linearity parameter, it can be seen that in general, the linearity of an SBS system improves in response to certain changes of the SBS parameters. For example, increasing the medium losses α, decreasing the Brillouin line centre gain factor g_0 (e.g. through polarisation [15]), decreasing the medium length L, or increasing the acousto-optic effective area A_{ao}, are all changes which, in general, will result in a more linear SBS amplifier, for a given amount of SBS gain $G(\nu)$. We state that this is the case in general because in fact, the expression for the linearity parameter is not monotonic.

IV. Results and Discussion

We set up an SBS-based microwave photonic filter as shown in Fig. 3, using different fibre lengths L to demonstrate the validity of the linearity parameter Υ in determining the linearity of an SBS system. SSB modulation was used because it allows for a direct mapping between the optical and electrical transfer function. In addition, an SSB-modulated optical signal is unaffected by the fibre dispersion, which is important when comparing systems where the optical signal has to travel along different lengths of fibre.

The laser diode (LD) used was a Santec wavelength-tunable, external cavity, semiconductor laser, with less than 500 kHz linewidth, operating at 1550 nm, and with an output power of 9.0 dBm. The light emitted from this laser was split using a 3 dB coupler. One half was injected into a modulator, where it underwent SSB modulation by an RF signal; the modulator had a switching voltage of 2.9 V. The resulting sideband was used as the Stokes wave for the SBS process. The pump wave was generated by sending the other half of the LD light to an optical frequency shifter (FS), where its frequency was down-shifted by 750 MHz. This was so that the SBS loss spectrum would not affect the filter passband generated by the SBS gain spectrum. A linear semiconductor optical amplifier (SOA), and an instrument erbium-doped fibre amplifier (EDFA) were used to independently adjust the power of the Stokes and pump waves, respectively, before they were made to counterpropagate in a spool of single-mode fibre (SMF). A second instrument EDFA was used at the output, just before the photodetector, to compensate for the medium losses encountered by the signal as it propagated in the SMF. These losses encountered both by the carrier and the sideband, being equal to $e^{-\alpha L}$, depended on the length of the SMF through which SBS occurred. For this reason, EDFA2 was used to maintain the optical power onto the photodetector fixed at 0 dBm, for different SMF lengths. Finally, since the modulator, the FS, and the SBS effect are polarisation dependent, standard polarisation controllers PC1, PC2, and PC3 were used to align the polarisation and minimise losses, as shown in Fig. 3.

The analysis in Section III showed that the design of the medium length can improve the linearity, hence the purpose of this experiment was to test the linearity of SBS amplification for different SBS medium lengths. This was done by using different lengths of SMF, in which SBS occurred. All the spools of SMF used had the same properties, namely $\alpha = 0.21$ dB/km, $A_{\mathrm{ao}} \approx 85\ \mu\mathrm{m}^2$, and $g_0 = 1.2 \times 10^{-11}$ m/W. The acousto-optic effective area was approximated with the optical effective area. This approximation has been shown to be accurate for fibres with a step-index profile [9], as was the case for our fibres. The Brillouin line centre gain factor was estimated through other experiments, and it included the effects of polarisation on the Brillouin gain. The relative state of polarisation between the pump and Stokes waves was controlled using the polarisation controller PC3. This was adjusted such that the filter stopband rejection level was maximised for a given pump power.

Since the optical power of the Stokes wave, i.e., the modulation sideband, is directly proportional to the power of the input RF signal, the linearity of the system was examined by applying different input RF powers to the filter. The power of the input RF signal was controlled through the vector network analyser (VNA). The gain of the SOA was kept constant throughout the whole experiment, so that the average optical power into the SMF remained constant at 4.3 dBm, while the optical sideband power could be controlled directly from the VNA. The gain of EDFA1, and thus the pump power, had to be adjusted for the different SMF lengths in order to realise a bandpass filter response with 30 dB stopband

TABLE I
EXPERIMENT MEASUREMENTS FOR A FILTER STOPBAND REJECTION LEVEL OF 30 DECIBELS

Length (km)	Pump Power (dBm)	3-dB cut-off (dBm)
25.32	6.0	−1.3
9.49	9.6	−0.9
2.01	14.5	3.2
0.57	20.0	8.4

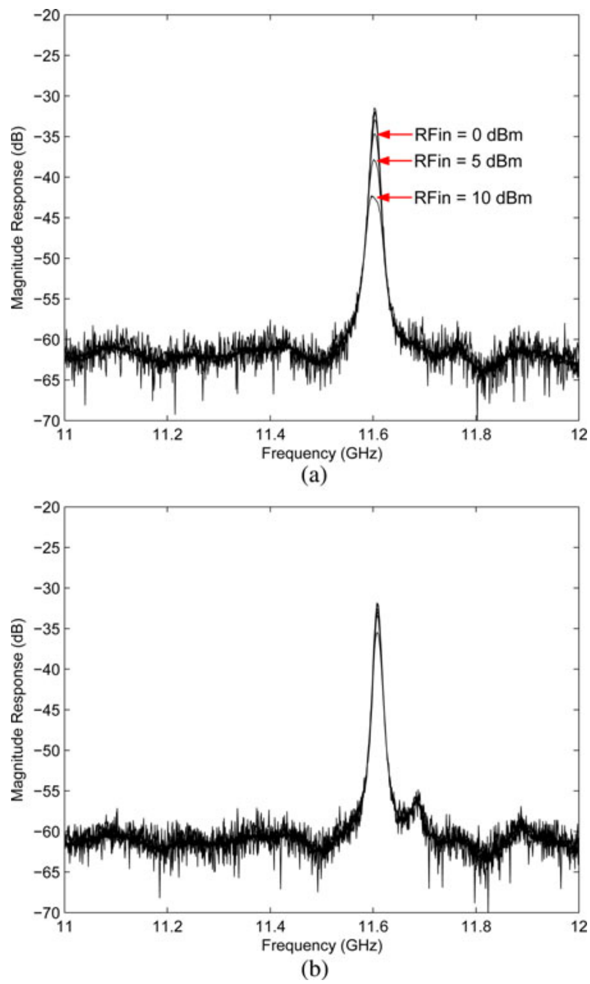

Fig. 4. Frequency response for input RF powers equal to −20 dBm, −15 dBm, . . ., 10 dBm. SMF length: (a) 25.32 km and (b) 0.57 km.

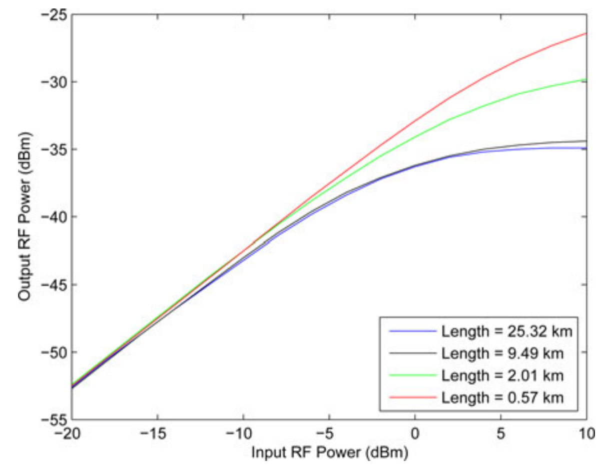

Fig. 5. Experimental input–output RF power relationship for different Brillouin medium lengths.

rejection level. The optical power at the output of EDFA1 for different fibre lengths is provided in Table I.

Four different fibre lengths of 25.32, 9.49, 2.01, and 0.57 km, all of them being of the same type and with the same optical properties, were tested. Initially, the pump power was adjusted so that in all cases, the filter stopband rejection level was 30 dB for −20 dBm input RF power. An illustration of the dependence of the rejection level on the input RF power is shown in Fig. 4, which shows the frequency response for the longest and shortest fibre lengths, for input RF powers ranging from −20 to 10 dBm, in increments of 5 dB. The stopband rejection level of the filter which used a fibre length of 25.32 km decreased from 30 dB, for an input RF power of −20 dBm, to 17 dB, for an input RF power of 10 dBm. When the fibre length was shortened to 0.57 km, the rejection level decreased by only 7 dB, over the same range of input RF powers. It is clear that for a shorter Brillouin medium length, the filter became much less dependent on the input RF power, and therefore, more linear.

In order to compare the linearity of the filter for different fibre lengths, the relationship between the input and output RF powers was measured. The procedure for this was to use a single-frequency RF signal as the input to the filter. The frequency of this RF signal was chosen to coincide with the centre frequency of the filter passband. The power of the RF signal at the output of the photodetector was measured using an electrical spectrum analyser. The results, shown in Fig. 5, clearly indicate that as the fibre length decreases, the linear region of the response extends over a wider range of input powers, and the dynamic range of operation increases.

The input and output RF power measurements were then used to show how the filter stopband rejection level changed for different input RF powers. The results were compared to simulations and are shown in Fig. 6. The response was normalised so that the stopband rejection level of the SBS-based filter operating in the linear region matched the one calculated, namely 30 dB.

These results, summarised in Fig. 7, clearly show that the linearity of the SBS process, and hence the filter, improve as the length of fibre where the Brillouin process takes place, is reduced. Our experiments show that the linear region of operation of the filter expands by 9.7 dB, as the fibre length is decreased from 25.32 km to 0.57 km. This improvement in linearity clearly comes at the cost of an increase in the Brillouin pump power required in order to achieve the same Brillouin gain, i.e., filter stopband rejection level. The properties of the filter for different fibre lengths are summarised in Table I. The measured pump power was compared to that predicted using (7). The result, plotted in Fig. 8, shows a close agreement with theory, especially for short fibre lengths. We believe that the discrepancy for longer fibre lengths is due to the fact that the 25.32 km and the 9.49 km fibre lengths were composed of a concatenation

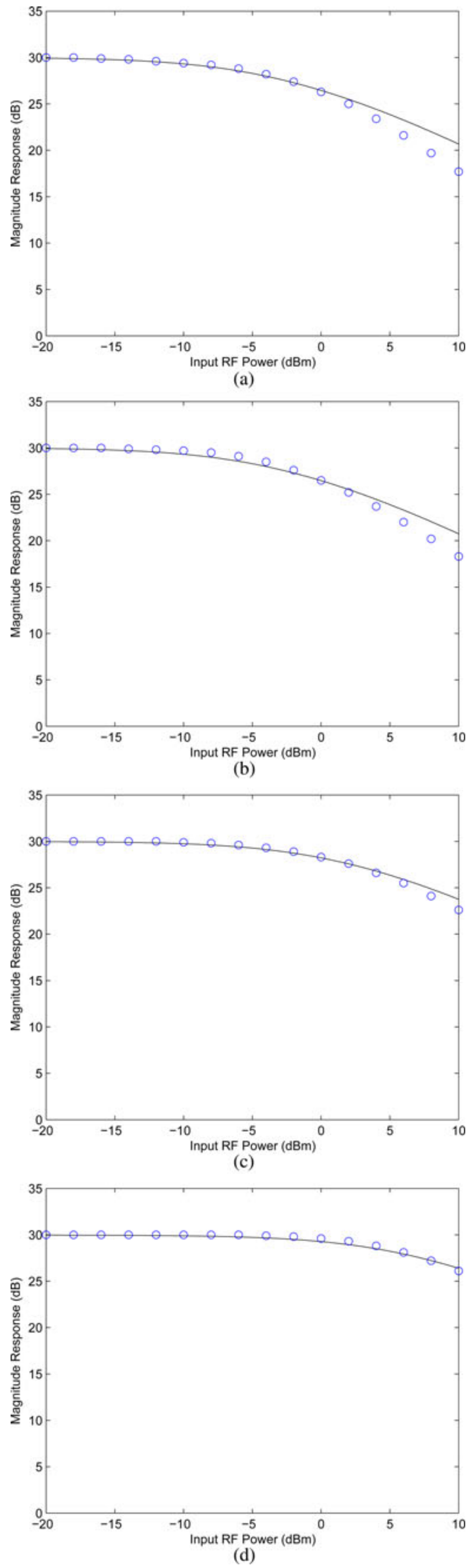

Fig. 6. Measured (circle) and simulated (line) filter rejection level for different input RF powers. SMF length: (a) 25.32 km, (b) 9.49 km, (c) 2.01 km, and (d) 0.57 km.

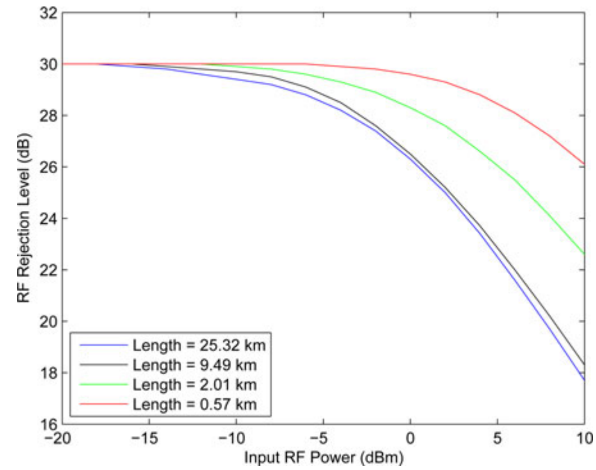

Fig. 7. Experimental filter rejection level for different Brillouin medium lengths.

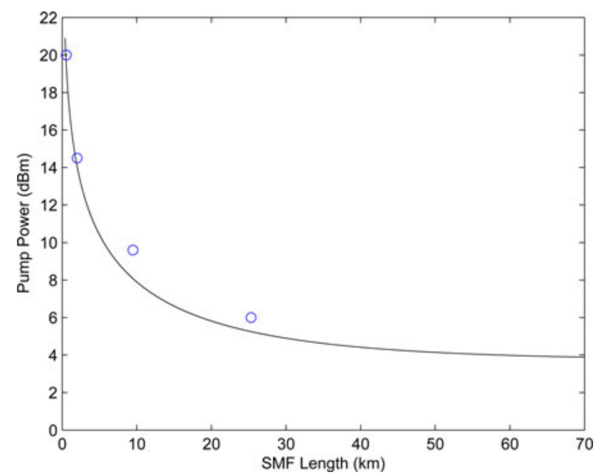

Fig. 8. Measured (circle) and simulated (line) pump power required to achieve 30 dB rejection level for different Brillouin medium lengths.

of multiple, shorter fibre lengths. This concatenation required the use of six and eight connectors to form the 9.49 km and the 25.32 km fibres respectively, thus introducing further losses. In addition, the modulator used to modulate the RF input onto the optical carrier could not achieve perfect SSB modulation, meaning that for longer fibre lengths, dispersion would cause the imperfectly suppressed sideband to interfere destructively with the main sideband, thus requiring more pump power to achieve a given amount of amplification. All these factors meant that for longer fibre lengths, the pump power required for the experiment was about 1 dB higher than that predicted theoretically.

The effect of the fibre length on the linearity of the filter, measured in terms of the input RF power at which the rejection level dropped 3 dB below its maximum value, is plotted in Fig. 9. Again, the experimental results are in close agreement with the values predicted using (10). As can be seen from this plot, the theory predicts that the filter linearity improves as the fibre length increases, although it improves at a faster rate for short fibre lengths. The main advantage of using longer fibre lengths would be that it decreases the Brillouin pump power required to achieve a given Brillouin gain.

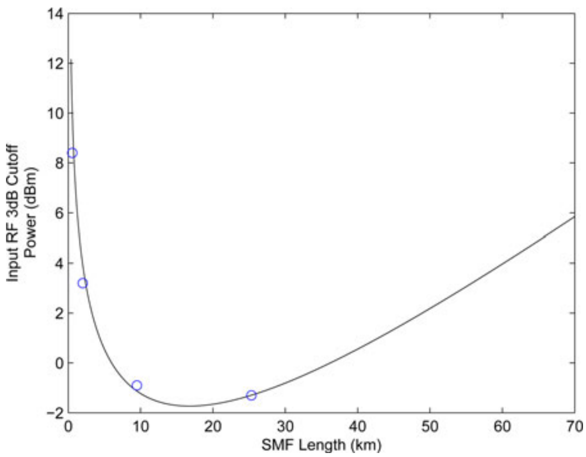

Fig. 9. Measured (circle) and simulated (line) input RF power at which the Brillouin gain drops by 3 dB below its maximum value of 30 dB, for different Brillouin medium lengths.

V. CONCLUSION

The linearity of SBS has been studied in detail for the first time, to the best of our knowledge. A closed form expression was derived, which measures how linear the SBS process is. This expression is in terms of system parameters which can usually be controlled, making it possible for the first time to be able to accurately predict and design the linearity of a system which employs SBS amplification.

The derived theory was tested in the form of experiments, in the context of microwave photonic filtering. The parameters that control the linearity of the SBS system have been identified and, in particular, a technique based on designing the optimum length of the medium through which SBS takes place has been shown to enable a significant improvement in the linearity of a microwave photonic filter. We successfully achieved an increase of 9.7 dB in the range of input RF powers in which the filter can be considered to be operating linearly. These results were found to be in close agreement with theory.

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Mattia Pagani received the B.E. degree in electrical engineering from the University of Sydney, Australia, in 2011, with the University Medal. He is currently working toward the Ph.D. degree from the Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), University of Sydney. His research interest includes microwave photonic signal processing, with emphasis on applications of stimulated Brillouin scattering.

Erwin H. W. Chan was born in Hong Kong in 1977. He received the B.Sc., B.Eng. (Hons.), and Ph.D. degrees from the University of Sydney, Australia, in 1998, 2000 and 2005, respectively. He is a Senior Research Fellow with the Fibre-Optics and Photonics Research Group and an External Lecturer with the University of Sydney. His research interests include microwave photonics, optical telecommunications, optical signal processing, and photonic and microwave technology. He has contributed more than 75 technical publications in which more than 40 are in the IEEE or OSA journals. Dr. Chan received the University of Sydney Early Career Development Award in 2005, and the Australian Postdoctoral Fellowship, awarded by the Australian Research Council in 2007. He was a member of the technical program committee of the Conference on Laser and Electro-optics (CLEO), and has been a Reviewer for more than 10 international scientific journals in the field of photonics, and optical communications.

Robert A. Minasian (S'78–M'80–SM'00–F'03) received the B.E. degree from the University of Melbourne, Melbourne, Australia, the M.Sc. degree from the University of London, University College, London, U.K., and the Ph.D. degree from the University of Melbourne. He is currently a Chair Professor with the School of Electrical and Information Engineering, University of Sydney, Australia. In addition, he is the Director of the Fibre-optics and Photonics Laboratory, and has also served as the Head of the School of Electrical and Information Engineering, University of Sydney. His research interests include optical signal processing and telecommunications, and currently centers on photonic signal processing, microwave photonics, broadband optical communications, and optical phased arrays. He has contributed more than 300 technical publications in these areas. He also holds several patents and has carried out consulting work with industry. He is an Associate Editor of *Optical Fiber Technology*. Dr. Minasian is a Fellow of the Optical Society of America. He is also a Fellow of the Institute of Engineers, Australia. He has served on the Australian Research Council as a member of the College of Experts. He is a member of the Technical Committee on Microwave Photonics of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), and has served and is on the program committees for several international conferences including the IEEE International Meeting on Microwave Photonics, the Asia Pacific Microwave Conference, the IEEE International Microwave Symposium, the Asia-Pacific Microwave Photonics Conference, and the IEEE LEOS Annual Meeting. He received the ATERB Medal for Outstanding Investigator in Telecommunications, awarded by the Australian Telecommunications and Electronics Research Board.