Role of amplified spontaneous emission in optical free-space communication links with optical amplification – impact on isolation and data transmission; utilization for pointing, acquisition, and tracking

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ABSTRACT

We investigate the role of amplified spontaneous emission (ASE) produced by an optical booster amplifier at the transmitter of free-space optical communication links. In a communication terminal with a single telescope for both transmission and reception, this ASE power has to be taken into account in connection with transmit-to-receive channel isolation, especially since it partly occupies the same state of polarization and the same frequency band as the receive signal. We show that the booster ASE intercepted by the receiver can represent a non-negligible source of background radiation: In a typical optical intersatellite link scenario, the ASE power spectral density generated by the booster amplifier at the transmitter and coupled to the receiver will be on the order of $10^{-20} W/Hz$, which equals the background radiation of the sun. Exploiting these findings for pointing, acquisition, and tracking (PAT) purposes, we describe a patent-pending PAT system doing *without* beacon lasers and *without* the need for diverting a part of the data signal for PAT. Utilizing the transmit booster ASE over a bandwidth of e.g. $20nm$ at the receiver, a total power of about $-46dBm$ is available for PAT purposes without extra power consumption at the transmitter and without the need for beacon laser alignment.

Keywords: amplified spontaneous emission (ASE); pointing, acquisition and tracking (PAT); noise; optical intersatellite link; optical free-space communications; on/off keying (OOK); background radiation; optical amplification; Erbium-doped fiber amplifier (EDFA).

1. INTRODUCTION

Over the past few years optical fiber amplifiers have become available with output power levels on the order of one Watt and higher. This technological breakthrough makes possible the use of such amplifiers as booster amplifiers in optical communication links (e.g. with Erbium-doped fiber amplifiers at a wavelength of $1.55\mu m$), where – unlike in terrestrial fiber-optic communication systems, where in-line amplifiers can be used – the power of the transmitter has to be sufficiently high to close the link. Furthermore, optical amplifiers with high gain and low noise figure are widely available today for use as optical preamplifiers within optical receivers, allowing to closely approach quantum limited performance.

It is the aim of this paper to investigate some fundamental issues brought by the use of optical booster amplifiers at the transmitter of an optical communication link. It will be shown in Section 2 that the amplified spontaneous emission (ASE) of the booster amplifier constitutes a source of background radiation that can well exceed the background radiation of the sun. The impact of this background term on the performance of an optically preamplified free-space communication link using on/off keying will be investigated in Section 3. It will be shown that the booster ASE limits the signal-to-noise ratio (SNR) up to communication distances of about $1000km$, causing the SNR to become independent of the communication distance up to that range. Section 4 is devoted to the problem of transmit-to-receive channel isolation in a full-duplex communication terminal within which transmitter and receiver have to share some optical components (e.g. the primary mirror of the transmit telescope). It is pointed out that severe

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technological problems are introduced by the need for suppressing the booster ASE. In Section 5, a novel, patent-pending pointing, acquisition and tracking (PAT) system making use of the otherwise unwanted and unused transmit booster ASE is proposed. It does *without* beacon lasers and *without* the need for diverting a part of the data signal for PAT.

2. AMPLIFIED SPONTANEOUS EMISSION OF THE BOOSTER AMPLIFIER AS A STRONG BACKGROUND SOURCE AT THE RECEIVER

Apart from the desired amplified input signal, optical amplifiers inherently emit a considerable amount of background radiation, the amplified spontaneous emission (ASE). It can be shown[1,2] that the ASE power spectral density $[W/Hz]$ is given by

$$N_{ASE} = hfGF/2\,, \tag{1}$$

where hf stands for the energy of one photon at the considered (optical) frequency, G denotes the optical amplifier's (power) gain, and F is the amplifier's noise figure, which ideally equals $3dB$. The ASE occupies the entire spectral range within which optical amplification is possible. It is frequency dependent, caused by variations of G and F with frequency. Note that equation (1) is valid for a *single* spatial mode (including polarization modes); in multimode applications N_{ASE} has to be multiplied by the number of emitted modes to arrive at the total ASE power spectral density. In practical optical communication links, the number of emitted modes will always be close to one, since all optical components (at the receiver as well as at the transmitter) are realized as close to diffraction-limit as possible to avoid high divergence of the transmit beam and to achieve a high coupling efficiency to the usually single-mode detection chain. In what follows, we assume an ideal, diffraction-limited system.

We proceed to calculate the ASE power generated by the optical booster amplifier and coupled to the receiver. To this end, consider the general setup of a typical optically boosted free-space communication link shown in Figure 1. The modulated transmit (TX) data are amplified by an optical booster amplifier with gain G_{TX} and noise figure

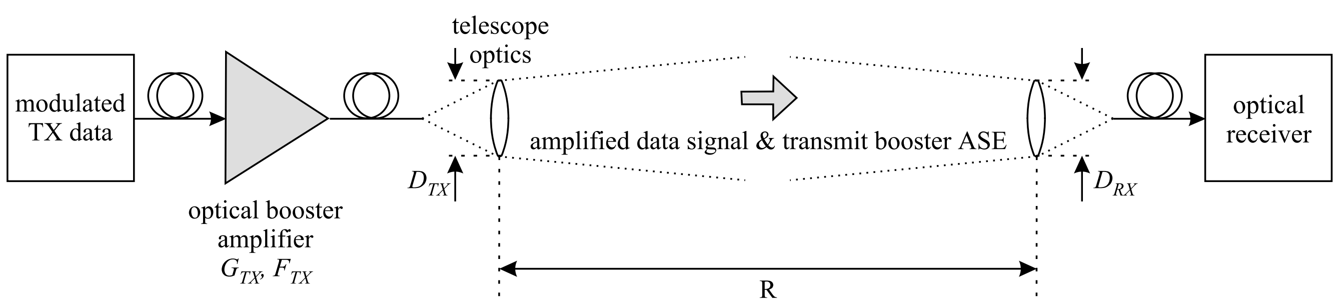

Figure 1. General setup of an optically boosted free-space communication link.

F_{TX} (usually realized in single-mode optical fiber technology) and transmitted by means of some telescope optics with clear diameter D_{TX}. The receive optics, situated a distance R apart, usually couples to an optical single-mode structure (such as an optical fiber).

It is well known[3] that the maximum on-axis gain of a centrally unobscured optical transmit antenna with respect to an isotropic radiator equals $0.81\pi^2 D_{TX}^2/\lambda^2$, where λ is the transmit wavelength. Also well known is the optimum value for the fraction of incident power that can be coupled to an optical fiber from an incident plane wave[4]; it amounts to 0.81. Thus, using equation (1), the ASE power spectral density generated by the booster amplifier and coupled to the receiver amounts to[*]

$$N_{ASE,\,TX\rightarrow RX} \approx 0.2hc\,G_{TX}F_{TX}D_{TX}^2 D_{RX}^2/(R^2\lambda^3)\,, \tag{2}$$

where c denotes the speed of light, and D_{RX} is the receive telescope diameter. Similarly, the signal power coupled to the receiver can be written as

$$P_{RX} \approx 0.41 P_{TX} D_{TX}^2 D_{RX}^2/(R^2\lambda^2)\,, \tag{3}$$

[*]Note that the temporal incoherence of the ASE does not affect propagation.

where P_{TX} represents the transmit power at the output of the transmit booster amplifier.

Taking typical values of available Erbium-doped booster amplifiers ($G_{TX} = 45dB$, $F_{TX} = 6dB$, $\lambda = 1.55\mu m$), telescope diameters $D_{TX} = D_{RX} = 10cm$, and a communication distance of $R = 4000km$, we arrive at $N_{ASE,TX\to RX} \approx 10^{-20}W/Hz$, which is of the order of magnitude of the background radiation per mode produced by the sun[5]! Taking the second strongest source of background radiation, Venus, which radiates with about $4 \cdot 10^{-25}W/Hz$ per spatial mode,[5] we find that the booster ASE constitutes the dominating background radiation term up to communication distances of $600\,000km$. – We thus conclude that the ASE produced by the booster amplifier at the transmitter of an optical communication link makes up an important source of background radiation at the receiver.

3. NOISE TERMS IN AN ON/OFF-KEYING COMMUNICATION LINK

The considerations presented so far were valid for any optically boosted communication system, regardless of the particular modulation format used. We now investigate the impact of the transmit booster ASE on the signal-to-noise ratio (SNR) – and thus implicitly on the bit error probability (BEP) – in an optically preamplified on/off keying (OOK) communication system, whose basic receiver structure is depicted in Figure 2. The received signal (of

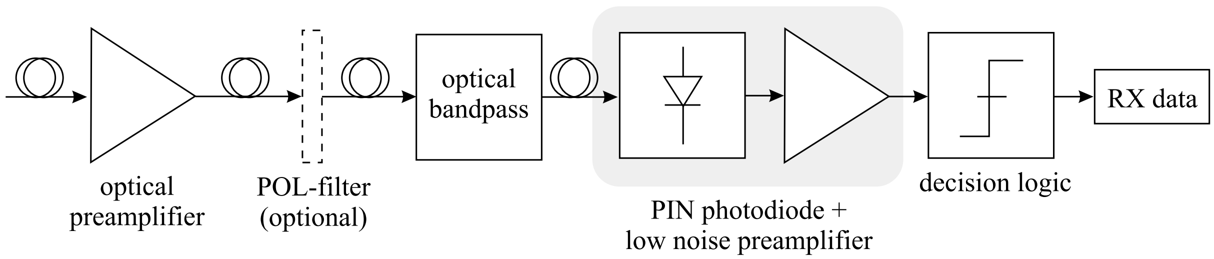

Figure 2. Basic block diagram of an optically preamplified on/off keying (OOK) receiver.

well-defined polarization) first passes an optical preamplifier. If a subsequent polarization filter can be used (which is only the case for a polarization maintaining optical preamplifier), one polarization mode of the preamplifier ASE can be suppressed. The optical bandpass preceding photodetection, too, reduces the detected preamplifier ASE power. A threshold detection device following the photodetector and the electrical preamplifier decides whether the received signal was a mark or a space.

Within a simple and reasonably accurate model for optical amplification, the ASE can be assumed to be a circularly symmetric complex Gaussian stochastic process.[2,6] Using standard semiclassical methods[7–9] the total variance of the photocurrent (= noise), σ^2_{total}, can be shown to read

$$\begin{aligned}\sigma^2_{\text{total}} &= \sigma^2_{\text{sig-shot}} + \sigma^2_{\text{back-shot}} + \sigma^2_{\text{ASE-shot}} + \sigma^2_{\text{dark-shot}} + \sigma^2_{\text{sig-back}} + \\ &+ \sigma^2_{\text{sig-ASE}} + \sigma^2_{\text{back-ASE}} + \sigma^2_{\text{ASE-ASE}} + \sigma^2_{\text{back-back}} + \sigma^2_{\text{electronic}} \,.\end{aligned} \tag{4}$$

The terms in (4) denote the following noise sources: The signal shot noise is

$$\sigma^2_{\text{sig-shot}} = 2eP_{RX,0/1}\,G_{RX}SB_e \,, \tag{5}$$

where e is the elementary charge, $P_{RX,0/1}$ is the optical power at the optical preamplifier input for a mark ($P_{RX,1}$) or a space ($P_{RX,0}$), G_{RX} is the gain of the optical preamplifier, S is the detector's responsivity $[A/W]$, and B_e is the receiver's electrical bandwidth. The shot noise produced by background radiation reads

$$\sigma^2_{\text{back-shot}} = 2eN_bB_oG_{RX}SB_e \,, \tag{6}$$

with B_o $[Hz]$ being the bandwidth of the optical bandpass filter. The variable N_b denotes the sum of all background power spectral densities $[W/Hz]$ at the optical preamplifier input. The preamplifier ASE-induced shot noise is given by†

$$\sigma^2_{\text{ASE-shot}} = (2\cdot)2eN_{ASE,RX}B_oSB_e \,, \tag{7}$$

†The abbreviation 'ASE' in the indices of the noise terms *always* denotes the *preamplifier* ASE, which must not be confused with the transmit booster ASE.

where $N_{ASE,RX}$ is the ASE power spectral density generated by the optical preamplifier; it can be calculated using equation (1). The multiplicative factor of 2 appearing in parentheses in (7) has to be taken into account only when *no* polarization filtering is performed after the optical preamplifier. The last shot noise term in (4) is induced by a photodiode dark current I_D,

$$\sigma^2_{\text{dark-shot}} = 2eI_D B_e \ . \tag{8}$$

The various beat noise terms have the following appearence: The signal-background beat noise reads

$$\sigma^2_{\text{sig-back}} = 4S^2 G^2_{RX} P_{RX,0/1} N_b B_e \ , \tag{9}$$

and the signal-preamplifier ASE beat noise term is

$$\sigma^2_{\text{sig-ASE}} = 4S^2 G_{RX} P_{RX,0/1} N_{ASE,RX} B_e \ . \tag{10}$$

Note that these terms are inherently *independent* of the additional use of a polarization filter‡. The background-preamplifier ASE beat noise term is given by

$$\sigma^2_{\text{back-ASE}} = 2S^2 G_{RX} N_b N_{ASE,RX} B_e (2B_o - B_e) \ , \tag{11}$$

and the beat noise term of the preamplifier ASE with itself reads

$$\sigma^2_{\text{ASE-ASE}} = (2\cdot) S^2 N^2_{ASE,RX} B_e (2B_o - B_e) \ , \tag{12}$$

where, again, the multiplicative factor of 2 takes account of the optional absence of a polarization filter. The background-background beat noise term is given by

$$\sigma^2_{i,\text{back-back}} = S^2 N_b^2 G^2_{RX} B_e (2B_o - B_e) \ . \tag{13}$$

The last – but in practical systems certainly not the least important – term is the additive electronic noise of the electrical preamplifier, $\sigma^2_{\text{electronic}}$. It is usually specified in terms of a density in $[pA/\sqrt{Hz}]$, referred to the electrical amplifier input.

In a practical system, not all the noise terms introduced above are significant. It can easily be shown – even for very conservative parameter sets – that $\sigma^2_{\text{ASE-shot}}$ can always be neglected compared to $\sigma^2_{\text{ASE-ASE}}$, and that $\sigma^2_{\text{dark-shot}}$ is by far smaller than $\sigma^2_{\text{sig-shot}}$, which itself is always much smaller than $\sigma^2_{\text{sig-ASE}}$. Similarly, the background shot noise term $\sigma^2_{\text{back-shot}}$ is always much smaller than $\sigma^2_{\text{back-ASE}}$.

As the total background radiation power spectral density N_b is the sum of the background radiation produced by celestial bodies and the transmit booster ASE,

$$N_b = N_b(R) = N_{\text{celestial bodies}} + N_{ASE,TX\to RX}(R) \ , \tag{14}$$

it is – like the received power P_{RX} – a function of the communication distance R (cf. equation (2)). It is thus interesting to study the dependence of signal and noise on R. Figure 3 shows the results for a $1.55\mu m$ communication system operating at $10Gbit/s$ with the following, realistic hardware parameters: The telescope diameters are $D_{TX} = D_{RX} = 10cm$, the transmit booster gain is $G_{TX} = 45dB$, its noise figure is $F_{TX} = 6dB$, and the transmit power for a mark is $P_{TX,1} = 25dBm$. The optical preamplifier at the receiver has a gain of $G_{RX} = 30dB$ and a noise figure of $F_{RX} = 3.5dB$; no polarization filter is used and the optical bandpass has a bandwidth of $70GHz$ ($\approx 0.6nm$). The photodiode sensitivity is $S = 0.8A/W$, the electrical bandwidth is $8GHz$, and the electrical preamplifier noise amounts to $12pA/\sqrt{Hz}$. The receiver is assumed to look directly into the sun, yielding a solar background radiation of about $10^{-20}W/Hz$. The thick lines in Figure 3 show the signal power i_1^2 and the total noise σ^2_{total} for a mark as a function of the communication distance R. The distance between the two curves gives the SNR; the required SNR for BEP$=10^{-9}$ is shown as a double arrow. All noise terms that contribute significantly to σ^2_{total} are drawn separately. It can clearly be seen that up to a link distance of $1000km$ the beating of the signal and the transmit booster ASE

‡From a semiclassical point of view, this ows to the fact that the signal power – occupying *one* polarization mode – only beats with *one* polarization mode of background or ASE radiation; a more elaborate explanation based on rigorous quantum mechanical reasoning can be found in Ref. 2.

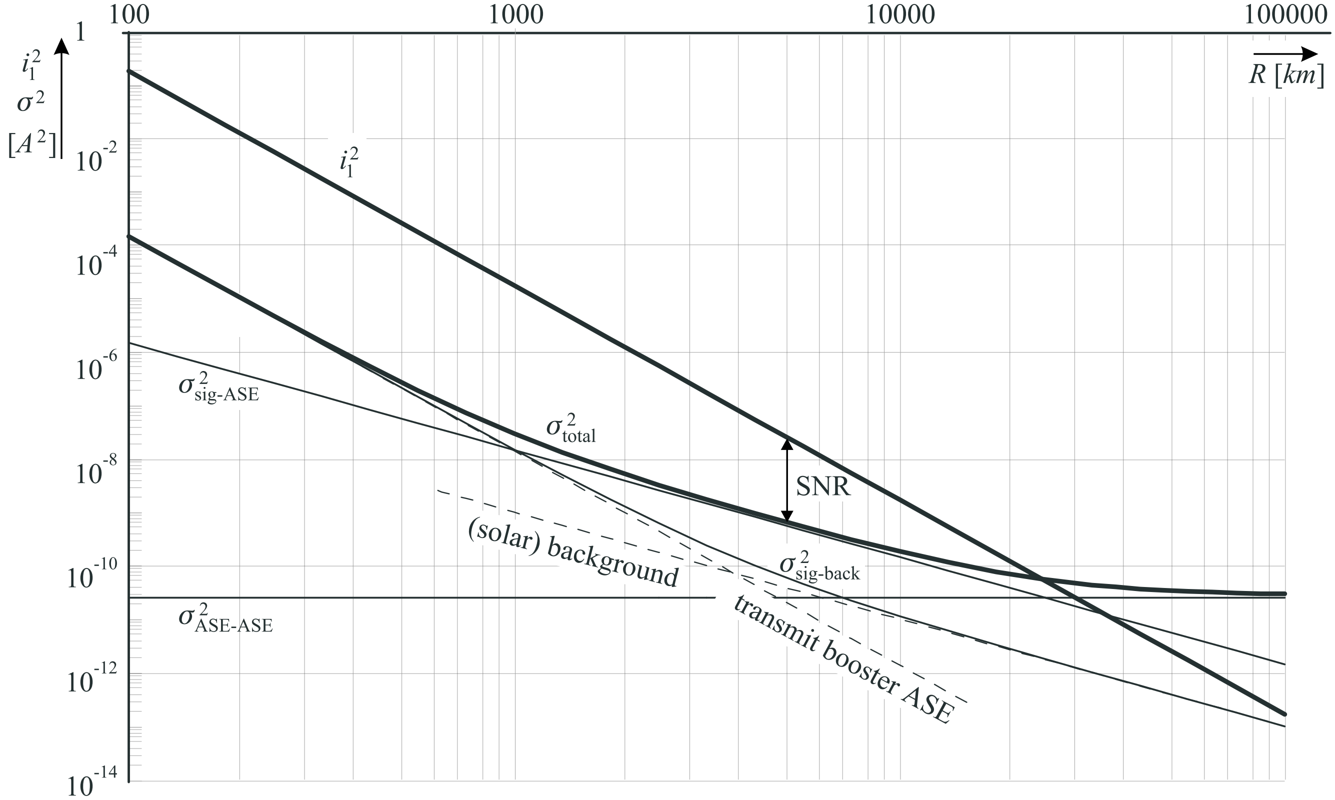

Figure 3. Signal power i_1^2 and total noise σ^2_{total} for a mark as a function of the communication distance R. The double arrow represents the required SNR for BEP$= 10^{-9}$. The noise terms contributing significantly to σ^2_{total} are drawn separately. Note that up to a link distance of $1000km$ the beating of the signal and the transmit booster ASE clearly dominates all other noise terms, causing the SNR to become *independent* of R.

dominates all other noise terms, causing the SNR to become *independent* of R. – The communication quality does in this case *not* increase with decreasing communication distance! Between $1000km$ and about $20\,000km$ the SNR is determined by the signal-preamplifier ASE beat noise and shows the familiar R^{-1} dependence. Above $20\,000km$ the ASE-ASE noise term comes into play, which causes the SNR to drop with R^{-2}. Note that background radiation as high as that of the sun never limits the SNR; this at first sight unexpected behaviour can be explained by the high gain of today's EDFAs and by the spatial filtering accomplished by coupling into single-mode fibers.

Concluding, it can be said that the transmit booster ASE has significant impact on the performance of a free-space communication link, especially at short link distances.

4. ISOLATION PROBLEMS BROUGHT BY THE TRANSMIT BOOSTER ASE

A conventional communication terminal consists of both a transmitter and a receiver that – necessitated by mass budget constraints – often share optical hardware (e.g. the primary telescope mirror). Care has to be taken in this respect that as little as possible of the terminal's transmit power enters the receive path of the terminal, i.e. proper *transmit-to-receive channel isolation* has to be aimed at. While systems working without booster amplifiers only have to suppress the narrow-band transmit signal lying well outside the receive frequency band, the use of optical booster amplifiers additionally requires suppression of the broad-band booster ASE radiation.

Figure 4 depicts a possible configuration to suppress both the fraction κ of the transmit signal and of the booster ASE that is scattered from the terminal transmitter to the receiver. The part κP_{TX} of the transmit signal scattered to the receive branch by optical elements shared by transmitter and receiver has to be attenuated such as not to saturate the optical preamplifier of the receiver. This can be done using an optical filter (filter A in Figure 4) in the receive branch that passes the receive frequency and attenuates the transmit frequency by a factor α. Further

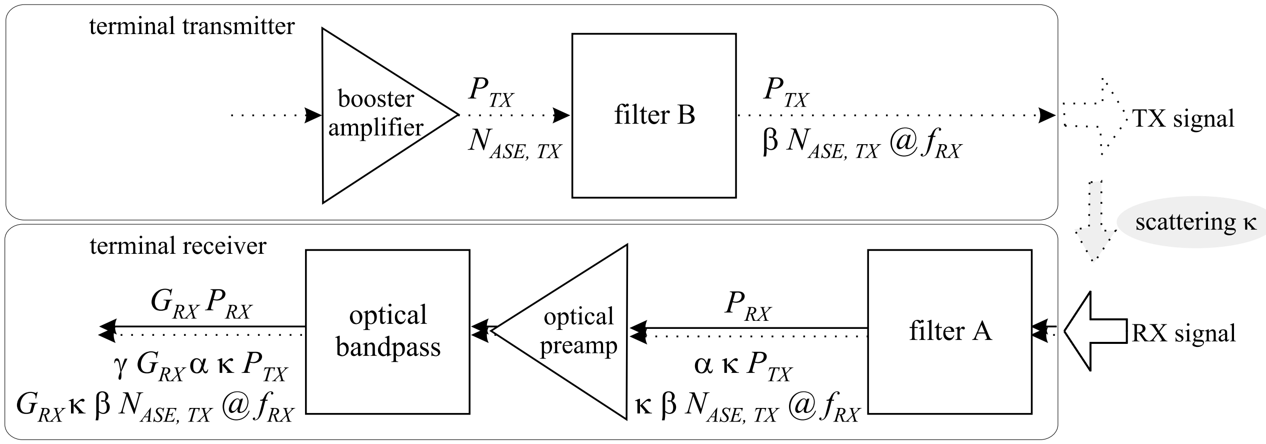

Figure 4. In order to reduce that part of the transmit signal power and of the booster ASE (dotted lines) that is coupled to the terminal receiver, two additional filters (filters A and B) are required. (α ... power transmission of filter A at the transmit frequency, β ... power transmission of filter B at the receive frequency, γ ... power transmission of optical bandpass at the transmit frequency, κ ... fraction of power in the terminal transmitter coupled to the terminal receiver, f_{RX} ... center frequency of receive signal)

suppression of the transmit signal below the receive signal (attenuation γ at the transmit frequency), as required by the detection circuitry, is then achieved by the bandpass filter following the optical receiver preamplifier. From equation 1, the ASE power spectral density of a typical Erbium-doped booster amplifier ($F = 6dB, G = 45dB$) can be estimated as $N_{ASE} \approx 8 \cdot 10^{-15} W/Hz$. This power spectral density has to be reduced to about $10^{-20} W/Hz$ in order to let the beating between signal and coupled booster ASE always lie below the beating of signal with the preamplifier ASE (cf. Figure 3). Thus, an attenuation of about $60dB$ is needed. Since the ASE power of the booster amplifier is emitted over a frequency band including the receive frequency, it can only be suppressed by a filter in the transmit branch (filter B in Figure 4). Assuming a crosstalk due to scattering of $\kappa \approx -30dB$, filter B has to have an attenuation of $\beta = 30dB$ in the receive band and *virtually no* attenuation in the transmit band, which poses severe technological problems, since the filter has to be inserted in the high-power transmit branch and thus has to withstand the immense output power of the booster amplifier. Filter A's insertion loss, on the other hand, directly decreases the receiver sensitivity, since it is located before the optical preamplifier.

In view of these findings, despite the mass and volume penalty, a spatial separation of the transmit and receive beams can well be the only alternative for a technical realization of an optically boosted communication terminal.

5. USING THE BOOSTER ASE FOR PAT

Having shown the presence of the transmit booster ASE at the receiver, its significance for evaluating the performance of a free-space optical communication link, and having pointed out the problems associated with transmit-to-receive channel isolation, we now present a way to *use* the otherwise unwanted booster ASE power for PAT purposes at the receiver; the proposed PAT system is patented.

One of the main tasks in optical communication links is the exact pointing and tracking of the transmit and receive telescopes.[10] The determination of pointing information used to align the direction of the telescopes as well as the retrieval of information on tracking data is usually done by means of separate laser sources (beacon lasers) or by means of splitting off a portion of the power-carrying data signal. The main disadvantages of the former method are, first, the need for additional components (implying additional power, mass, and complexity), and, second, the required stable and accurate alignment of the beacon laser with the transmit and/or receive directions. The latter method demands higher transmit power levels than would be necessary to close the communication link itself (if PAT could be done in a different way), which can quickly lead to technological limits.

The transmit booster ASE has two properties that can be advantageously used for designing a PAT system at the receiver:

1. The ASE spectrum exceeds that of the data signal by orders of magnitude; it occupies the entire spectral range within which optical amplification is possible and can thus be almost entirely separated from the data signal by wavelength-dependent optical elements. Thus, the entire signal power can be used for communication purposes, whereas the otherwise unused booster ASE power or some part of it may be used for PAT[§].

2. As the ASE occupies the same spatial mode(s) as the data signal, both fields are automatically co-aligned and experience the same propagation conditions.

A possible realization of the PAT system is shown in Figure 5: The incident optical field is focused by means of the telescope optics. Using a frequency selective beam splitter (which need not necessarily have the bandpass/bandstop characteristics schematically suggested in Figure 5, but may equally well be realized as a highpass/lowpass filter), the major part of the ASE power is diverted to the PAT system. After angular magnification (e.g. by means of a telescope structure), which serves to increase the angular resolution of the system, the ASE power is detected at e.g. a quadrant error sensor (a CCD sensor would equally well be possible). The output of these detectors is directly used to generate the control signals for the telescope pointing/tracking unit.

As was shown in Section 2, the ASE power spectral density of an EDFA transmit booster coupled to the receiver of a realistic system with a communication distance of $4000km$ approximately equals $10^{-20}W/Hz$. Using the ASE within a spectral region of about $20nm$ (the spectral width of the ASE is about $30nm$ for an EDFA booster), we arrive at some $25nW$ ($-46dBm$) optical power available for PAT purposes, which compares well with the PAT power of other systems.[11]

6. CONCLUSIONS

The ASE produced by the transmitter of an optically boosted communication link constitutes a non-negligible source of background radiation at the receiver. For typical hardware parameters and a communication distance of $4000km$, the power spectral density of the booster ASE is still as strong as that encountered when looking directly into the sun ($\approx 10^{-20}W/Hz$ per spatial mode). At a communication distance of $600\,000km$ the booster ASE is still comparable to the background radiation of Venus ($\approx 4 \cdot 10^{-25}W/Hz$ per spatial mode).

We investigated the impact of the transmit booster ASE on the performance of an optically preamplified free-space communication link and showed that the booster ASE limits the SNR up to communication distances of about $1000km$, causing the SNR to become independent of the communication distance in that range.

In addition to the problem of suppressing that part of the transmit signal that is scattered to the receiver of a full-duplex communication terminal within which transmitter and receiver have to share optical components, isolation of the booster ASE invokes the need for an optical filter in the high-power transmit path, which poses severe technological problems. Complete separation of the optical paths (and thus the use of two separate telescopes) can well be the only viable alternative in an optically boosted terminal.

The broadband ASE emitted by the booster amplifier at the transmitter of an optical free-space communication link can advantageously be used for PAT purposes at the receiver. The proposed, patent-pending PAT-method eliminates the need for using separate power or hardware (including mass, complexity and cost) for beacon lasers, taking care of alignment procedures between the beacon-lasers and the transmit or receive telescopes, and splitting off a certain fraction of the information carrying data signal for PAT purposes. A further definite advantage is the simple splitting mechanism of the data signal and the ASE power at the receiver using a single, state-of-the art optical component (e.g. a wavelength-dependent beam splitter).

7. ACKNOWLEDGEMENTS

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[§]In principle, one can also envisage a splitting between signal and booster ASE employing the polarization properties of the two optical fields.

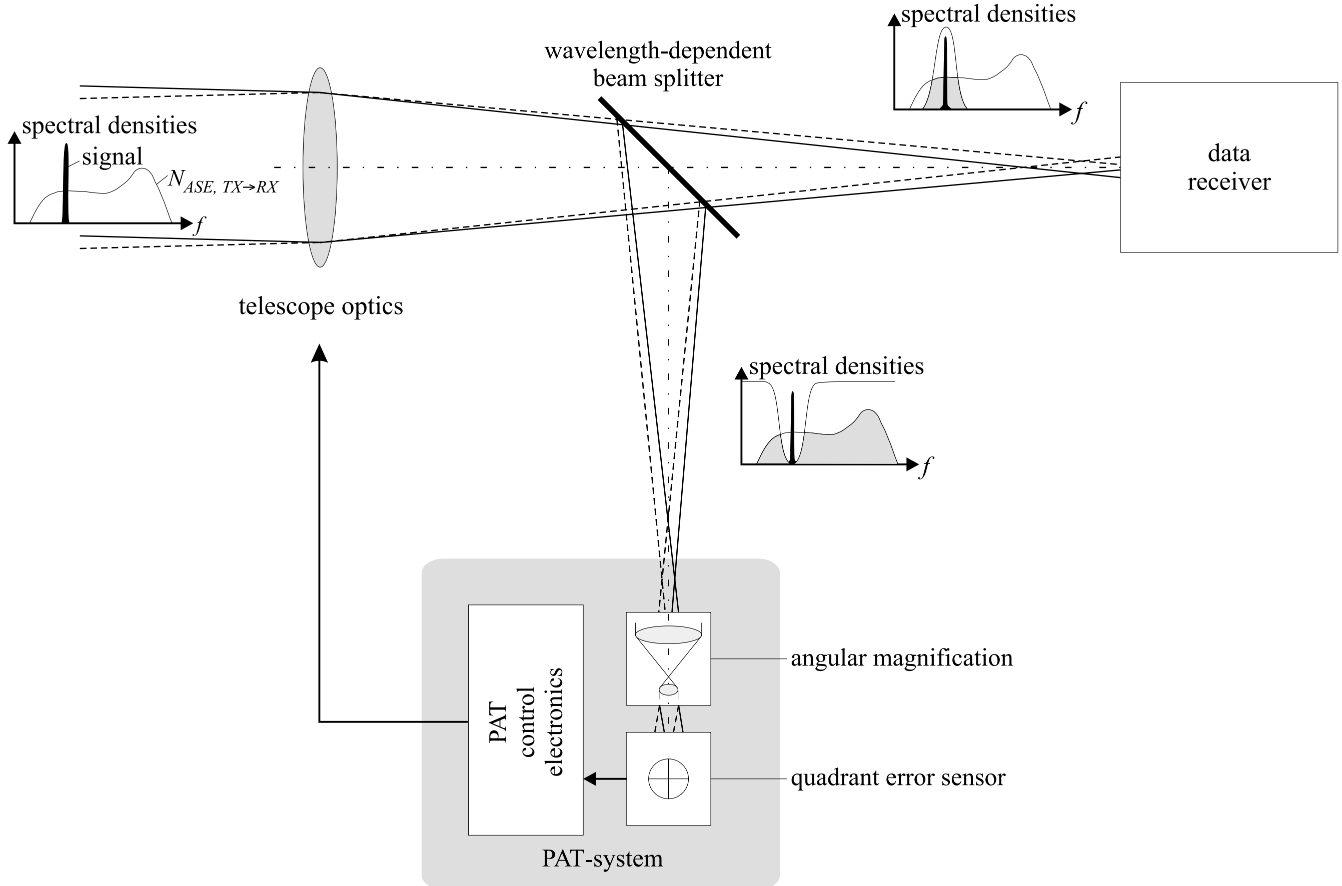

Figure 5. Possible realization of a PAT system that retrieves the pointing/tracking information from the ASE emitted by the booster amplifier at the transmitter.

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