Noise reduction in plasmonic amplifiers

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Surface plasmon polaritons amplification gives the possibility to overcome strong absorption in metals and design truly nanoscale devices for on-chip photonic circuits. However, the process of stimulated emission in the gain medium is inevitably accompanied by spontaneous emission, which greatly increases the noise power. Herein we present an efficient strategy for noise reduction in plasmonic amplifiers which is based on gain redistribution along the amplifier. We show that even a very small gain redistribution (~3%) makes it possible to increase the signal-to-noise ratio by ~100% and improve the bit error ratio by orders of magnitude. © 2018 The Japan Society of Applied Physics

In the past two decades, advances in nanophotonics and plasmonics have brought optical communications to the nanoscale, where they can meet the exponentially growing demand for high-speed and high-throughput communication.1–4 The capacity for signal amplification is one of the key requirements for reliable data transmission and detection.5 At the nanoscale, optical amplification can be provided by active nanophotonic6,7 or plasmonic structures.8–11) The latter provide the opportunity to bridge the scale gap between the on-chip electronic and optical components. However, this opportunity comes at the price of increased internal optical losses attributed to absorption in the metal, which is an essential component of plasmonic devices. The modal loss increases rapidly as the mode confinement becomes stronger.12,13) Nevertheless, remarkable progress on plasmonic nanolasers and amplifiers9,10,14–19) shows that a net optical amplification can be achieved even in plasmonic waveguides with deep-subwavelength confinement. However, the problem is that every optical amplifier adds spontaneously emitted photons to the signal-carrying mode.20) The stochastic nature of the spontaneous emission process manifests itself as photonic noise that produces photocurrent fluctuations at the photodetector.21,22) Because plasmonic amplifiers operate at very high degrees of population inversion,19) the spontaneous emission rate is considerably higher than that in photonic amplifiers, and so is the noise power.23,24) This strong noise leads to errors on the receiver side, which can greatly decrease the information capacity of the data transmission channel and render it useless.

Here, we present a strategy to greatly improve the noise characteristics of nanoscale plasmonic amplifiers by controlling the spatial distribution of the modal gain along the amplifier. The proposed method of noise reduction does not affect the net amplifier gain and can be easily implemented in practical devices, as we demonstrate numerically using the example of a practical metal/semiconductor amplifier.

Noise added by an optical amplifier is produced by intensity fluctuations due to interference between the spectral components of the signal propagating in the amplifier and the amplified spontaneous emission (ASE) generated by the gain medium. Depending on which spectral components interfere, two contributions can be distinguished: the signal–spontaneous beat noise and the spontaneous–spontaneous beat noise.20,21) In contrast to optical fiber amplifiers, nanoscale active plasmonic structures feature a very high ASE power, which can significantly exceed the power of the transmitted signal. Therefore, the power of the spontaneous–spontaneous beat noise, which does not depend on the signal power, can be much stronger than that of the signal–spontaneous beat noise.23) A narrow band-pass filter between the amplifier and receiver can solve this problem by reducing the noise power density S to that produced only by the interference of the signal and the ASE at the carrier frequency of the signal, $\nu_0$:

$$S(f) = -\frac{4e^2}{h} \frac{P_{\text{out}}}{\nu_0^2} \rho_{sp}(\nu_0),$$

where $h$ is the Planck constant, $e$ is the elementary charge, $\rho_{sp}(\nu_0)$ is the spectral power density of the ASE at the output of the amplifier, $P_{\text{out}}$ is the signal power at the output of the amplifier, and $f$ is the noise frequency, which is limited by the $RC$ rise time of the receiver circuit (~0.1 ns). Further, $\rho_{sp}(\nu_0)$ depends strongly on the distribution of the modal loss $\alpha(z)$ and modal gain $G(z)$ along the amplifier. The rate of spontaneous emission of the gain medium into the signal-carrying mode per unit amplifier length is equal to

$$R_{sp}(\nu_0, z) = \frac{2}{h} G(z) N_{sp}(z),$$

where $N_{sp}$ is the spontaneous emission factor of the gain medium. $N_{sp}$ is defined as the ratio of the spontaneous emission rate into the signal-carrying mode to the stimulated emission rate per photon in the same mode. In subwavelength plasmonic waveguide structures, the propagation loss is typically as high as 500–5000 cm$^{-1}$ (Refs. 9, 10, and 25). Therefore, one has to provide a very high gain ($G > \alpha$), which can be created only under strong population inversion. However, a positive material gain in the active medium is unavoidably accompanied by strong spontaneous emission. As the population inversion becomes stronger, the spontaneous emission rate increases. For example, in a semiconductor active medium,

$$N_{sp} = \left[1 - \exp \left(\frac{h \nu_0 - (F_z - F_h)}{k_B T} \right) \right]^{-1},$$

where the difference $(F_z - F_h)$ between the quasi-Fermi levels characterizes the population inversion. At a high material gain, $(F_z - F_h - \nu_0) \gtrsim 2k_B T$, and therefore, $N_{sp} \approx 1$. The spectral power density of the ASE at the output of the amplifier can be found by integrating $R_{sp}(\nu_0)$ over the amplifier length. Here, we should note that the spontaneously emitted surface plasmons are also amplified by the plasmonic amplifier, which adds the propagation factor $\exp \left[ \int_{z_1}^{z_2} \left( G(z') - \alpha(z') \right) dz' \right]$, and only half of the spontaneously emitted surface...
The problem is that in nanoscale plasmonic structures, the modal loss $\alpha$ is very high. Therefore, it is not possible to create a modal gain much higher than $G_0 = \alpha$. Nevertheless, by combining stronger amplification ($G_0 + \Delta G$) in the first half of the amplifier and weaker amplification ($G_0 - \Delta G$) in the second half (Fig. 2), it is possible to reduce the noise power.

Let us consider a realistic truly nanoscale plasmonic amplifier and evaluate the influence of the gain redistribution on its noise characteristics. Figure 2(a) shows a cross-section of the amplifier, which is based on an active T-shaped plasmonic waveguide. The substrate is made of a ternary AlAs$_x$Sb$_{1-x}$ alloy lattice matched to the In$_{x}$Ga$_{1-x}$As gain medium. An In$_{x}$Ga$_{1-x}$As/AlAs$_x$Sb$_{1-x}$ heterojunction is used to confine injected electrons and holes to the active region. An $x$ value of 0.52 is chosen to match the peak wavelength of the gain spectrum of In$_{x}$Ga$_{1-x}$As to the free-space signal wavelength, $\lambda = 1550$ nm. A 2-nm-thick insulator layer (such as HfO$_2$) between the metal and semiconductor is required for efficient injection of electrons from the metal through a tunnel metal–insulator–semiconductor junction. Copper is chosen to form a surface-plasmon-supporting interface owing to its outstanding optical properties at $\lambda = 1550$ nm (Refs. 30 and 31). The waveguide shown in Fig. 2(a) is single-mode and supports only the fundamental plasmonic mode strongly confined to the Cu/HfO$_2$/InGaAs contact, which is confirmed by direct finite element simulations using COMSOL Multiphysics. The modal loss $\alpha$ is found to be $790$ cm$^{-1}$, and the mode confinement factor to the active region is 1.09. The moderate value of the modal loss compared to other semiconductor plasmonic waveguides...
with similar dimensions predetermines good noise performance. Such an active plasmonic waveguide can be pumped either optically or electrically. However, a detailed discussion of the pump mechanisms is outside the scope of the present letter and will be published elsewhere. Here, we focus on the noise characteristics. We start by considering the amplifier with $P_{\text{out}}/P_{\text{in}} = 1$, which corresponds to the case in which high propagation losses ($\alpha = 970\,\text{cm}^{-1}$) are fully compensated by the gain in the semiconductor ($G_0 = \alpha$). This regime enables high-speed data transmission over a long distance via a truly nanoscale waveguide. The amplifier length is set to $L = 1\,\text{mm}$, which is a typical length of global on-chip interconnects.

The ASE spectral power density, which determines the noise power, is directly calculated from the simulated material gain spectrum and spontaneous emission rate in InGaAs, which are found using the densities of nonequilibrium electrons and holes (for the methods, see Refs. 23 and 28). Figure 3(a) clearly shows that the noise power decreases with increasing $\Delta G$. At $\Delta G = 1000\,\text{cm}^{-1}$ ($\Delta G/G_0 \approx 100\%$), the beat noise is reduced by a factor of 42 from the initial level and reaches a noise level that is only 4.7 times higher than the fundamental limit established by Eq. (6). On the other hand, if we exchange the amplifying and attenuating halves of the amplifier (i.e., change the sign of $\Delta G$ to negative), the noise power at the output increases significantly [Fig. 3(a)]. At a relatively small $\Delta G = -100\,\text{cm}^{-1}$ ($\Delta G/G_0 \approx -10\%$), the noise is 30 times stronger than at $\Delta G = 0$. Notably, this noise increase is much stronger than the noise decrease at $\Delta G = 100\,\text{cm}^{-1}$ ($\Delta G/G_0 \approx +10\%$) [Fig. 3(a)].

It is important to note that by redistributing the modal gain, one also changes the spontaneous emission rate [see Eq. (2)] and consequently the ASE power at the output of the amplifier. By integrating Eq. (3) over the entire spectra of the spontaneous emission and modal gain and taking into account the fact that spontaneously emitted surface plasmon quanta propagate in both directions of the amplifier, we obtain the spatial distribution of the ASE power in the amplifier [Fig. 3(b)]. The ASE power at the output of the amplifier decreases as $\Delta G$ increases, which is beneficial for practical applications [Fig. 3(b)]. However, the ASE power inside the amplifier increases with $\Delta G$. At $\Delta G = 100\,\text{cm}^{-1}$ ($\Delta G/G_0 \approx 10\%$), it reaches 2 mW, which is 20 times higher than the maximum ASE power at $\Delta G = 0$ (100 $\mu$W). Such a high ASE power is extremely undesirable because the ASE depletes the carrier density in the active medium and therefore increases the power consumption. Moreover, the ASE is absorbed in the metal, which increases the heat generation rate in the amplifier.

Although it is difficult for the amplifier to operate at high $\Delta G$ owing to the high ASE power in the amplifier, even a small gain redistribution is beneficial for the design of practical devices. A $\Delta G$ value as low as 25 cm$^{-1}$ ($\Delta G/G_0 \approx 2.6\%$) makes it possible to reduce the noise power by 40%. In this case, the maximum ASE power is only 30% higher than that in the amplifier with no gain redistribution. It is noteworthy that by placing an attenuating region ($G < G_0$) before the amplifying region ($G > G_0$), one only degrades the amplifier performance because both the ASE power and noise level are increased compared to those of the amplifier with a homogeneous gain distribution (Fig. 3).

The noise power is directly related to the bit error ratio (BER), which is the percentage of bits transmitted or detected incorrectly. Because $\log(\text{BER}) \propto 1/S$ (Refs. 21 and 33), a twofold reduction in the noise power corresponds to an improvement of at least 4 orders of magnitude in the BER in low-quality communication channels ($\text{BER} \sim 10^{-5}$). On the other hand, if the quality of the communication channel is high at $\Delta G = 0$ (BER $< 10^{-9}$), the BER decreases by 8 orders of magnitude when we slightly redistribute the modal gain in the plasmonic amplifier ($\Delta G/G_0 \approx 3\%$).

The strategy for noise reduction based on gain redistribution can be applied with no change to amplifiers with any net amplification coefficient $P_{\text{out}}/P_{\text{in}}$ (Fig. 4). Note, however, that as the net amplifier gain increases, the influence of the gain redistribution on the noise power slightly decreases (Fig. 4).
In summary, we investigated plasmonic amplifiers with a modal gain that is nonuniformly distributed along the amplifier and evaluated the influence of the gain distribution on the noise characteristics for the first time. We showed that the noise power can be greatly reduced by slightly increasing the modal gain in the first half of the amplifier and decreasing it in the second half of the amplifier at a fixed net amplification coefficient $P_{\text{out}}/P_{\text{in}}$. Although the strong gain redistribution required for noise suppression is difficult to implement in practical devices owing to the very high ASE power in the amplifier, even a very small gain redistribution ($\Delta G/G_0 \approx 3\%$) makes it possible to reduce the noise power by approximately 50%. Because the BER of communication depends exponentially on the signal-to-noise ratio, this noise reduction increases the reliability of communication by more than four orders of magnitude. These numbers can be further improved by optimizing the modal gain distribution. However, the optimization should be performed with respect to both the energy efficiency and the signal-to-noise ratio, because the increased ASE power greatly increases the power consumption of the amplifier. Thus, the proposed strategy for noise reduction makes it possible to improve the noise characteristics of plasmonic amplifiers at nearly no cost, opening new avenues in the design and development of nanoscale optical amplifiers for deep-subwavelength nanophotonic circuits.

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