New GAWBS Noise Interacting with Longitudinally Propagating Acoustic Waves in Few-mode Fibers

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Abstract: We describe the GAWBS noise characteristics in few-mode fibers (FMFs). We found that the GAWBS noise is newly generated due to an interaction between different LP modes through longitudinally propagating acoustic waves. © 2024 The Author(s)

1. Introduction

3M technology based on multi-level modulation and space-division multiplexing (i.e., multi-core and multi-mode fibers) has attracted much attention as a promising approach for a significant increase in the transmission capacity of a single optical fiber [1]. Recently, fiber capacities exceeding 10 Pbit/s have been demonstrated using 19-core, 6-mode [2] and 38-core, 3-mode [3] fibers. In a long-haul coherent transmission using 3M technology, it has been revealed that guided acoustic-wave Brillouin scattering (GAWBS) noise [4, 5] is one of the factors in performance degradation [6-12]. The GAWBS noise characteristics in single-mode fibers (SMF) [13-15] and multi-core fibers [16, 17] have already been reported in detail, where a "cross-sectional acoustic wave" was the origin of the GAWBS noise. On the other hand, although the GAWBS noise spectrum in few-mode fibers (FMFs) has been observed [18, 19], the noise characteristics have not yet been clarified.

In this paper, we present the GAWBS noise characteristics in FMFs. First, we measured the GAWBS noise in a two-LP-mode fiber and found that the $R_{0,m}$ acoustic modes cause not only phase noise but also intensity noise for the LP_{11} mode as a result of mode-coupling between the degenerate LP_{11a} and LP_{11b} modes. Then, by extending the mode number to a general FMF case, for example six-LP-mode fiber, we clarify that the GAWBS noise is newly generated due to an interaction between the different LP modes through "longitudinally propagating acoustic waves".

2. GAWBS noise in FMFs

Thermally excited acoustic waves in the cross section of an optical fiber cause a dielectric constant change $\Delta\varepsilon$ in accordance with the photoelastic effect. Then, $\Delta\varepsilon$ causes mode-coupling between two eigenmodes (E_μ, E_ν) in the fiber [20]. The mode-coupling coefficient is given by [15, 21]

$$\kappa_{\mu\nu} = -i\frac{k_0}{2n_0\varepsilon_0}\frac{\int_0^{2\pi}\int_0^a\left\{E_\mu(r,\theta)\Delta\varepsilon(r,\theta)E_\nu(r,\theta)\right\}rdrd\theta}{\int_0^{2\pi}\int_0^a\left\{E_\mu(r,\theta)E_\nu(r,\theta)\right\}rdrd\theta}. \quad (1)$$

Here, k_0 is the propagation constant, ε_0 is the permittivity in free space, and a is the fiber radius. In eq. (1), the coupling coefficient is expressed as not a real but an imaginary number. Thus, the mode-coupling induces the optical phase change. In SMF, since there is only one mode ($E_\mu = E_\nu$), the optical phase change is given as follows.

$$\delta\phi = k_0 l\frac{\int_0^{2\pi}\int_0^a\left\{\Delta n(r,\theta)E_\mu^2(r,\theta)\right\}rdrd\theta}{\int_0^{2\pi}\int_0^a E_\mu^2(r,\theta)rdrd\theta} \quad (2)$$

Here, l is the fiber length, Δn ($=\Delta\varepsilon/2n_0\varepsilon_0$) is the refractive index change caused by an acoustic mode. Eq. (2) is well known as the GAWBS phase noise. However, the GAWBS noise characteristics in FMF may be significantly different from those in SMF since the mode-coupling between different LP modes will occur according to eq. (1).

First, we measured the GAWBS noise spectrum in a 38.6 km-long FMF supporting two LP modes using delayed self-heterodyne detection. The FMF had a cladding diameter of 125 μm, and A_{eff} values of 114.1 and 151.6 μm^2 for the LP_{01} and LP_{11} modes, respectively [22]. The crosstalk between the LP_{01} and LP_{11} modes was less than - 20 dB, it was small enough to be negligible for the GAWBS noise measurement. The measurement setup is shown in Fig. 1. As a continuous wave (CW) light source, we used a fiber laser with a linewidth of 4 kHz, which is sufficiently narrower than the

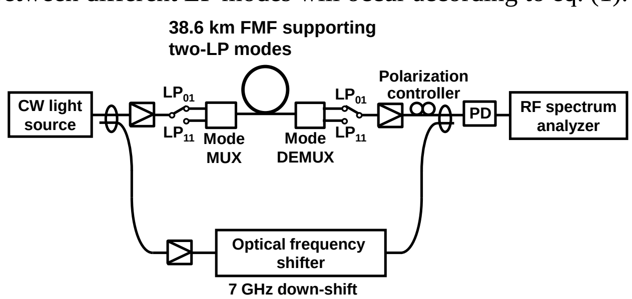


Fig. 1. Experimental setup for measuring GAWBS phase noise spectra in a 38.6 km-long FMF supporting two LP modes.

linewidth of the GAWBS noise spectrum (~ MHz). The CW carrier was split into two paths, and one signal was launched into the FMF. The other was used as a local oscillator (LO) after downshifting the frequency by 7 GHz, which enabled heterodyne detection. We observed the intermediate frequency (IF) signal with an RF spectrum analyzer.

We measured the GAWBS phase noise spectra generated in the FMF when the LP_{01} and LP_{11} modes were launched individually via a mode-multiplexer. We selectively detected the LP_{01} or LP_{11} mode via a mode-demultiplexer at the receiver. Figure 2 shows the GAWBS phase noise spectra obtained by detecting the excited LP mode, where we measured the GAWBS phase noise for $LP_{01}\rightarrow LP_{01}$ and $LP_{11}\rightarrow LP_{11}$. Here, the calculated results of the GAWBS phase noise induced by the $R_{0,m}$ acoustic modes using eq. (2) are also plotted with circles. In the GAWBS noise spectrum for the LP_{01} mode shown in Fig. 2(a), the profile was almost the same as that generated in SMFs and agreed well with the calculation results. In contrast, the spectral profile of the LP_{11} mode had two lobes as shown in Fig. 2(b), and noise components in the high frequency region above 300 MHz were larger than the numerical calculation results.

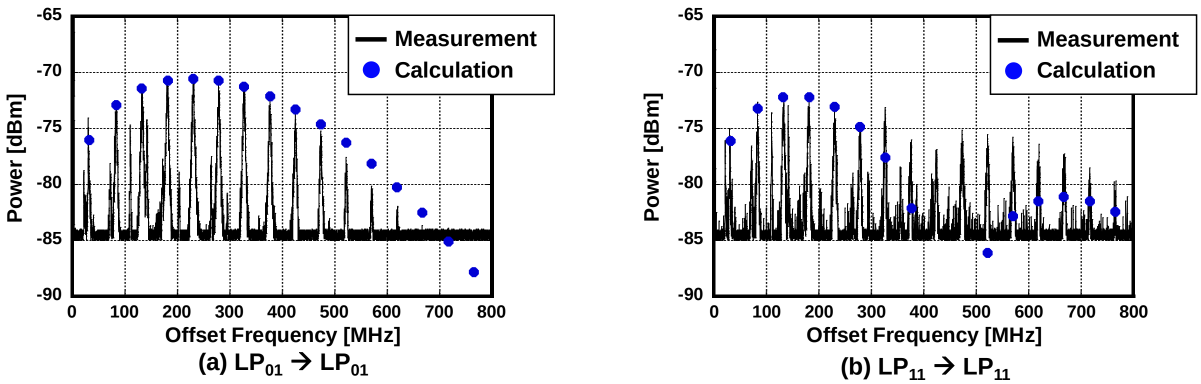


Fig. 2. GAWBS phase noise spectra observed in a 38.6 km-long FMF when the LP_{01} and LP_{11} modes were excited individually.

To find the origin of the noise generated above 300 MHz, we detected the intensity modulation components of the optical carrier transmitted in the FMF by direct (intensity) detection. The direct detection spectrum is shown in Fig. 3, where noise components corresponding to Fig. 2(b) were observed in the frequency region above 300 MHz. Here, the circles in Fig. 3 show the coupling power between the degenerate LP_{11a} and LP_{11b} modes calculated by substituting the dielectric constant change due to the $R_{0,m}$ acoustic modes into eq. (1), which agreed well with the measured spectrum. Although the interaction of the $R_{0,m}$ acoustic modes causes the optical phase change, it is converted into intensity noise through the linear mode-coupling between the degenerate LP_{11a} and LP_{11b} modes in FMF. These results indicate that the $R_{0,m}$ acoustic modes cause not only phase noise but also intensity noise for the LP_{11} mode.

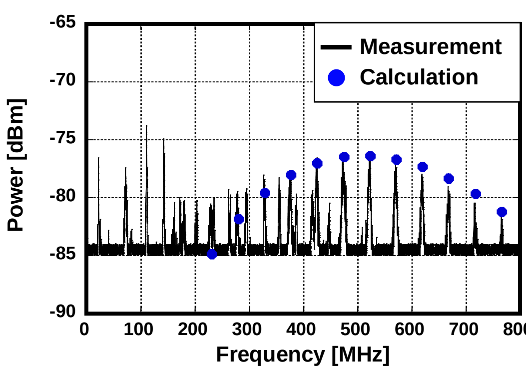


Fig. 3. Direct detection spectrum of an optical carrier transmitted in a 38.6 km-long FMF for $LP_{11} \rightarrow LP_{11}$.

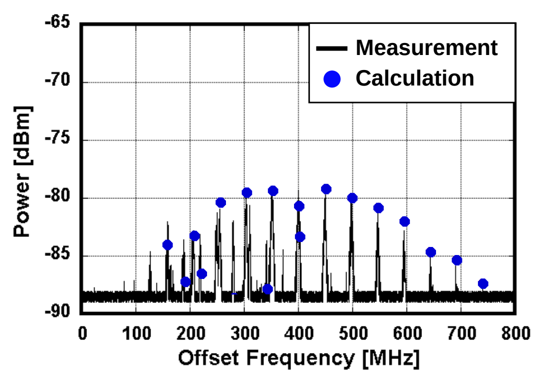
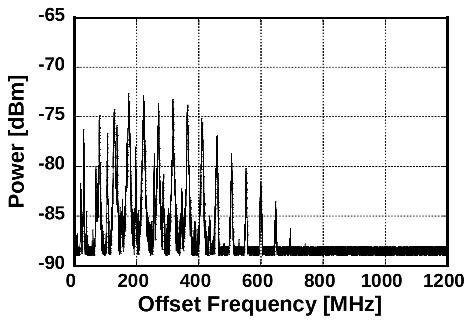


Fig. 4. GAWBS phase noise spectrum observed in a 38.6 km-long FMF for $LP_{01} \rightarrow LP_{11}$

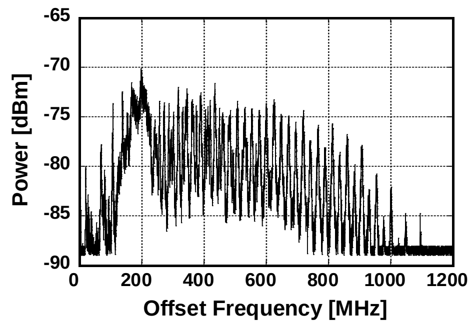
Figure 4 shows the GAWBS phase noise spectrum when we detected the unexcited LP mode with a mode-demultiplexer, which corresponds to $LP_{01}\rightarrow LP_{11}$ plotted with a solid line. The circles also show the coupling power between the LP_{01} and LP_{11} modes calculated by substituting the dielectric constant change due to the $TR_{1,m}$ acoustic modes into eq. (1), which agreed well with the measured spectrum. This means that there is an interaction between the LP_{01} and LP_{11} modes through the $TR_{1,m}$ acoustic modes with the axial wave vector (i.e. longitudinally propagating acoustic waves), which leads to phase matching between these LP modes. Note here that this phenomenon does not occur as a result of linear crosstalk (- 20 dB) between LP_{01} and LP_{11} modes.

As described above, we found that GAWBS noise is newly generated due to an interaction between the different LP modes through longitudinally propagating acoustic waves in FMF. This indicates that the total power of the GAWBS noise will increase as the number of LP modes in the FMF increases.

Next, to confirm our thought, we measured the GAWBS noise characteristics in a 48 km-long FMF supporting six LP (LP_{01}, LP_{11}, LP_{21}, LP_{02}, LP_{31}, and LP_{12}) modes [23] using the same setup as in Fig. 1. Figure 5 shows the GAWBS phase noise spectra obtained by detecting the LP_{01} mode via a mode-demultiplexer. When only the LP_{01} mode was excited as shown in Fig. 5(a), the spectral profile was almost the same as that obtained with the two-LP-mode fiber shown in Fig. 2(a). On the other hand, when all six LP modes were simultaneously excited as shown in Fig. 5(b), many GAWBS noise components were newly generated through mode-couplings from the other LP modes. The observed spectrum agreed well with our calculation.



(a) $LP_{01} \rightarrow LP_{01}$



(b) LP_{01}, LP_{11}, LP_{21}, LP_{02}, LP_{31}, $LP_{12} \rightarrow LP_{01}$

Fig. 5. GAWBS phase noise spectra observed in a 48 km-long FMF supporting six LP modes when we detected the LP_{01} mode.

We calculated the GAWBS noise coefficient Γ from the power ratio of the IF signal to the total noise power for both sidebands. When only the LP_{01} mode was excited as shown in Fig. 5(a), the calculated Γ was -31.5 dB/Mm. This result indicates that since the A_{eff} of FMF is larger than that of standard single-mode fiber (SSMF: A_{eff} = 80 μm^2, Γ = -29.7 dB/Mm [15]), the GAWBS noise coefficient is relatively low. On the other hand, when all six LP modes were simultaneously excited as shown in Fig. 5(b), the total noise coefficient increased to as much as -25.7 dB/Mm, which is 4 dB larger than that of SSMF.

Although the A_{eff} of FMF is large, where the ordinary GAWBS noise coefficient is low, it should be noted that when there are mode-couplings between different LP modes, the total GAWBS noise largely increases through phase-matching with the longitudinally propagating acoustic waves.

3. Conclusions

We found that a new GAWBS noise is generated in FMFs through mode-couplings between different LP modes. This suggests that the GAWBS noise is more significant in a space-division multiplexed transmission when using an FMF supporting many LP modes than that in SMF.

Acknowledgements

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