All-fiber acousto-optic frequency shifter

B. Y. Kim and J. N. Blake

Edward L. Ginzton Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, Stanford, California 94305

H. E. Engan

Division of Physical Electronics, The Norwegian Institute of Technology, N-7034 Trondheim, Norway

H. J. Shaw

Edward L. Ginzton Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, Stanford, California 94305

Received January 27, 1986; accepted March 24, 1986

An all-fiber-optic frequency shifter is demonstrated that uses mode coupling between the LP_{01} and LP_{11} modes by a traveling acoustic flexural wave guided along the optical fiber. The input and output leads of this frequency shifter are single-mode fibers. Unity mode-conversion efficiency for cw operation is achieved at 8-MHz frequency shift with about 0.25 W of electrical input power. Carrier and image sideband suppression of 15 and 35 dB, respectively, are demonstrated.

Single-sideband optical frequency shifters in waveguide form have been sought for many years for use in fiber-optic systems such as gyroscopes, heterodyned sensors, signal processing, and coherent communications. By replacing its bulk-optic counterpart (Bragg cell) with a guided-wave frequency shifter, one can make such fiber-optic systems mechanically rugged and compact, and critical optical alignment procedures can be avoided. A number of different approaches have been demonstrated that use either birefringent optical fibers[1,2] or integrated-optical waveguides.[3–5] These devices make use of periodic optical coupling between two orthogonal polarization modes that have different propagation velocities in a single-mode waveguide using acousto-optic or electro-optic effects or take the form of a serrodyne frequency shifter in which a linear phase ramp simulates frequency shifting. Integrated-optical devices were demonstrated with broad bandwidth and better than 30-dB sideband suppression, but reduction of relatively high insertion loss of the devices and further suppression of unwanted sidebands are yet to be seen. Fiber-optic frequency shifters with similar sideband suppression have also been demonstrated that use a traveling acoustic wave and high-birefringence fiber, but they require a large acoustic energy to achieve good optical coupling efficiency.

In this Letter, we report an all-fiber-optic single-sideband frequency shifter utilizing periodic optical coupling between two spatial modes in circular optical fibers, instead of two polarization modes, with the coupling provided by a traveling acoustic wave guided by the optical fiber. In contrast to frequency shifters using high-birefringence fiber, the present device does not require any critical angular alignments of fiber axes or other components. Also, since the optical fiber actually guides the acoustic wave, the acoustic energy can be more efficiently employed without compromising the carrier and sideband suppression ratios.

With a weakly guiding approximation, the two lowest-order modes of an optical fiber are the LP_{01} and LP_{11} modes with propagation constants of β_{01} and β_{11} ($<\beta_{01}$), respectively. In an unperturbed straight fiber, these two modes are orthogonal to each other, and they do not exchange optical power as they propagate along the fiber. An efficient coupling between these modes can be obtained by introducing periodic microbending whose period matches the beat length between them ($L_B = 2\pi/\Delta\beta$, where $\Delta\beta = \beta_{01} - \beta_{11}$), thus providing the phase-matching condition.[6,7] When the periodic microbending is a traveling wave, an optical signal that is coupled from one mode to the other by this wave is frequency shifted, as is well known for other types of guided-wave frequency shifters.[2,4] Traveling periodic microbending can be generated by exciting an acoustic flexural wave traveling along the optical fiber. The optical signal coupled from the slow mode (LP_{01}) to the fast mode (LP_{11}) will be downshifted in frequency by an amount equal to the acoustic frequency when the acoustic flexural wave is traveling in the same direction as the optical signal. Frequency upshift will take place for the coupling from the fast mode to the slow mode for the same acoustic wave. The sign of frequency shift will be reversed when the acoustic wave is traveling in the opposite direction to that of the optical signal.

A schematic diagram of the proposed acousto-optic frequency shifter is shown in Fig. 1. Both the input and output ends of this device are single-mode fibers that are connected to a double-mode fiber that supports the LP_{01} and LP_{11} modes. The key elements of this frequency shifter are mode filters for the LP_{01} and LP_{11} modes and an acoustic transducer that excites traveling microbends (flexural mode) guided along the optical fiber. A mode filter that strips the LP_{11} mode can be realized by wrapping the fiber around a circular cylinder with proper diameter or by adiabatically tapering the core diameter of a section of the fiber. The

0146-9592/86/060389-03$2.00/0

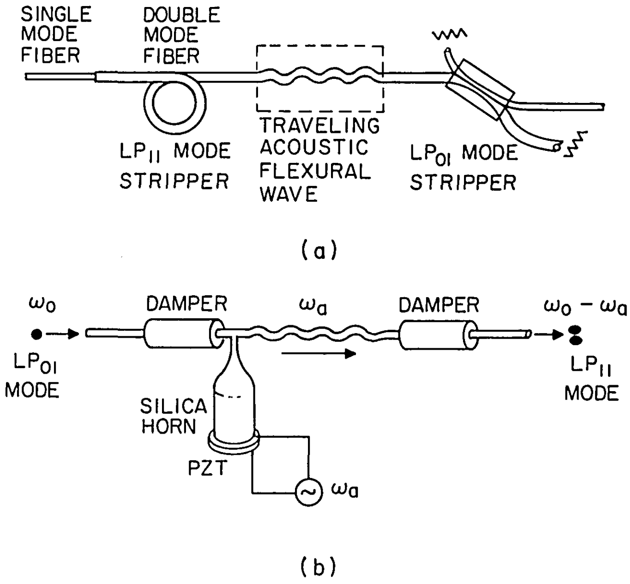

Fig. 1. (a) Schematic diagram of an all-fiber-optic frequency shifter with mode filters for the LP$_{01}$ and LP$_{11}$ modes and a traveling acoustic flexural wave. (b) Frequency shifting in a double-mode fiber using intermodal coupling by an acoustic flexural wave excited by an acoustic horn.

LP$_{01}$ mode stripper can take the form of an evanescent-field directional coupler constructed with a double-mode fiber and a single-mode fiber, where only the LP$_{11}$ mode in the double-mode fiber can couple to the single-mode fiber.[8] In this case, the propagation constant of the guided mode in the single-mode fiber matches well with that of the second-order mode in the double-mode fiber to permit complete optical power transfer between these modes. The propagation-constant mismatch and smaller optical field overlap between the two fundamental modes suppress optical power coupling between them. 24 dB of isolation between the LP$_{11}$ and LP$_{01}$ modes has been demonstrated with this type of mode filter.

The acoustic transducer was designed to displace transversely a short section of the fiber perpendicular to its axis such that a flexural acoustic wave is excited, which travels along the fiber. The wavelength of this flexural wave should match the beat length L_B between the two optical modes. One way of accomplishing this is to use a cylindrical acoustic horn made of silica glass bonded to a piezoelectric transducer (PZT) on one end and to the fiber on the other end, as illustrated in Fig. 1(b). This configuration permits concentration of the acoustic intensity generated by the PZT into a higher acoustic intensity signal at the tip of the horn. Therefore a large excursion of the tip can be obtained with low acoustic power. By making the diameter of the tip of the horn that is bonded to the fiber approximately the same as that of the fiber, a good acoustic energy transfer can be achieved. The bonding between the fiber and the horn can be done by direct fusion or by using other bonding materials. To prevent the acoustic wave from traveling in both directions or to limit the acousto-optic interaction length, acoustic dampers can be used, as indicated in Fig. 1(b). Since the acoustic energy is confined within the fiber, the acoustic energy density can be high, permitting efficient acousto-optic coupling.

Let us consider an optical input from the single-mode fiber that is spliced to the double-mode fiber [left-hand side of Fig. 1(a)]. By aligning the centers of the two cores, one can excite mostly the LP$_{01}$ mode in the double-mode fiber. The small amount of excited LP$_{11}$ mode will be suppressed further by the mode stripper so that only the LP$_{01}$ mode enters the interaction region. Because of the microbending that is traveling along the fiber in the same direction as the optical wave, optical energy is coupled to the LP$_{11}$ mode and its frequency is downshifted by the acoustic frequency. The optical signal that has not coupled and retains the original frequency will not be coupled to the single-mode fiber when it arrives at the directional coupler on the right-hand side of Fig. 1(a). Therefore the light that is tapped into the single-mode fiber contains only the shifted frequency component. The same effect will be achieved for an optical input from the single-mode fiber that is coupled to the double-mode fiber through the directional coupler on the right-hand side of Fig. 1(a), making this frequency shifter a reciprocal device. Only the LP$_{11}$ mode will be excited in the double-mode fiber, and it will be coupled to the LP$_{01}$ mode and downshifted in frequency as it interacts with the acoustic flexural wave that is traveling in the opposite direction to the optical wave. The unshifted frequency component in the LP$_{11}$ mode will be attenuated by the mode stripper. Therefore the optical signal that is coupled into the single-mode fiber at the left contains only the frequency-shifted component.

A prototype frequency shifter using intermodal coupling through a traveling acoustic flexural wave as shown in Fig. 1 was built and characterized. The double-mode fiber used for frequency shifting had an outer diameter of 85 μm, a core diameter of 4.6 μm, and an LP$_{11}$ mode cutoff wavelength of 671 nm. The optical source wavelength was 488 nm, and the beat length between the two modes at this wavelength was measured to be about 265 μm. The measurement tech-

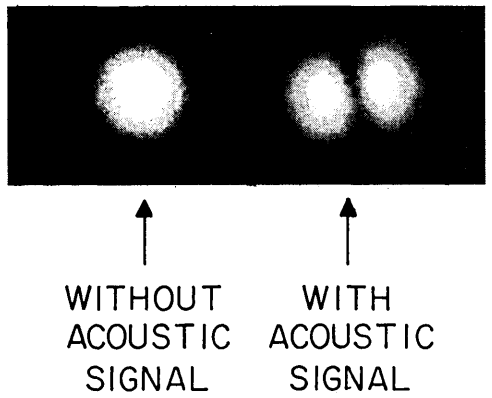

Fig. 2. Far-field radiation pattern showing mode conversion (LP$_{01}$ mode to LP$_{11}$ mode) due to the traveling acoustic flexural wave guided by an optical fiber.

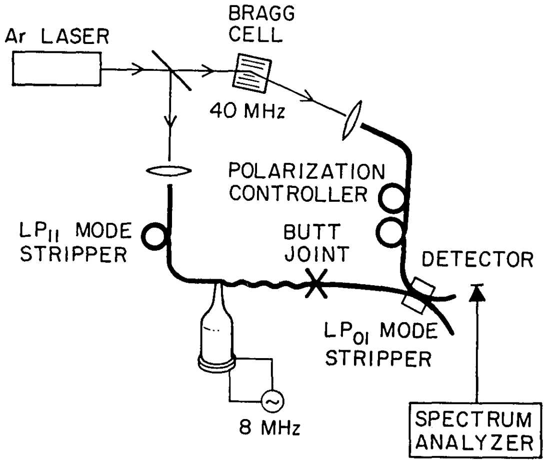

Fig. 3. Experimental setup for evaluation of the frequency shifter.

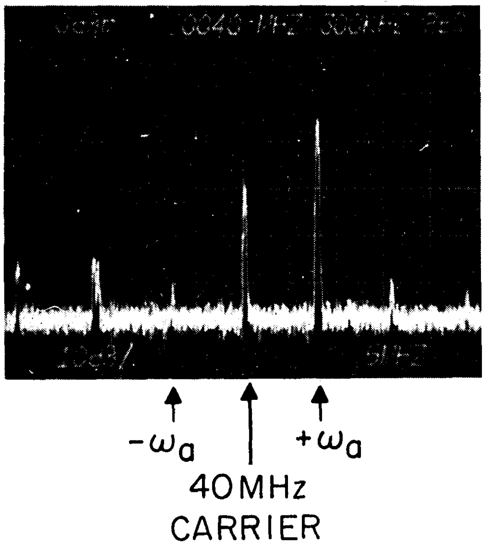

Fig. 4. Experimental result showing the sideband suppression.

niques for the beat length between the two modes are described in Refs. 7 and 9. One end of a piece of 2-mm-diameter silica glass rod was melted and pulled to form a glass horn having a tip with about 100-μm diameter. The tip of the horn was then securely bonded to the fiber to form a T by using a glass with a low melting temperature (softening temperature of about 500°C). The other end of the glass horn was bonded to a PZT designed to excite a longitudinal acoustic wave in the horn. The plastic protective jacket of the fiber served as the acoustic damper. The length of the bare fiber was about 7.5 cm, which defined the maximum interaction length. The LP$_{11}$ mode stripper was made by wrapping 15 turns of the fiber around a 0.64-cm-diameter post. The acoustic frequency that produced the maximum intermode coupling was about 8 MHz. At this frequency, a coupling efficiency of unity was achieved with about 0.25 W of electric power applied to the PZT. First, this device was tested as a simple mode coupler without the LP$_{01}$ mode stripper. Figure 2 shows the change in the far-field radiation pattern from the end of the double-mode fiber used for the frequency shifting, with and without the acoustic wave excited in the fiber. A complete coupling between the two modes can be seen. We also observed overcoupling when the acoustic power was increased further.

In order to measure the carrier and image sideband suppression, a heterodyned Mach–Zehnder interferometer was constructed as shown in Fig. 3. A Bragg cell with 40-MHz frequency shift is used for heterodyning. Although a single strand of double-mode fiber should have been used for the construction of the mode filters and the frequency shifter, a separate LP$_{01}$ mode stripper was spliced to the double-mode fiber used for acousto-optic frequency shifting for the present demonstration. This LP$_{01}$ mode stripper could not efficiently discriminate the shifted frequency component from the unshifted one. This resulted in a poor optical carrier suppression because the two modes were mixed at the splice. The double-mode fiber in the mode filter was not the same as the one used for the frequency shifting. The experimental result is shown in Fig. 4. It can be seen that sideband suppression of about 35 dB and carrier suppression of about 15 dB were achieved. Higher-order sidebands generated from dc and 40 MHz are also seen. We noticed that most of the error originated from the imperfect mode filters.

In summary, we have demonstrated an all-fiber-optic frequency shifter, for the first reported time, that uses acousto-optic intermodal coupling in a double-mode fiber. Optical carrier and sideband suppression of 15 and 35 dB, respectively, are demonstrated. This device can also be used as an optical amplitude modulator or a switchable directional coupler. Further studies on acoustic transducers, mode filters, and operational bandwidth of the frequency shifter are under way.

We wish to thank J. Vrhel and D. Walsh for transducer fabrication. This research was supported by Litton Systems, Inc.

References

1. K. Nosu, S. C. Rashleigh, H. F. Taylor, and J. F. Weller, Electron. Lett. **19**, 816 (1983).
2. W. P. Risk, R. C. Youngquist, G. S. Kino, and H. J. Shaw, Opt. Lett. **9**, 309 (1984).
3. K. K. Wong, R. M. De La Rue, and S. Wright, Opt. Lett. **7**, 546 (1982).
4. F. Heismann and R. Ulrich, Appl. Phys. Lett. **45**, 490 (1984).
5. L. M. Johnson, Proc. Soc. Photo-Opt. Instrum. Eng. **566**, 96 (1985).
6. H. F. Taylor, J. Lightwave Technol. **LT-2**, 617 (1984).
7. J. N. Blake, B. Y. Kim, and H. J. Shaw, Opt. Lett. **11**, 177 (1986).
8. W. V. Sorin, B. Y. Kim, and H. J. Shaw, "Highly selective evanescent modal filter for two-mode optical fibers," submitted to Opt. Lett.
9. W. V. Sorin, B. Y. Kim, and H. J. Shaw, Opt. Lett. **11**, 106 (1986).