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REFERENCES

Precision Timing Control for Radioastronomy
Maintaining Femtosecond Synchronization in the Atacama Large Millimeter Array

JEAN-FRANÇOIS CLICHE and BILL SHILLUE

The Atacama Large Millimeter Array (ALMA) (see Figure 1) is an international radio astronomical facility currently under construction in Chile through the collaboration of institutions in the United States, Canada, Europe, and Japan [1]. When completed, the facility will consist of an array of up to 64 12-m parabolic antennas that can detect millimeter and submillimeter wavelength radio waves in the frequency band between 31–950 GHz. The antenna will be located at an elevation of 5,000 m on the Chajnantor plain in the district of San Pedro de Atacama. At these wavelengths, the radiotelescope array will be able to reveal the structure of the cold regions of the universe, otherwise dark at visible wavelengths, with unprecedented sensitivity and a resolution of 10 milliarcseconds. This resolution is an order of magnitude better than the Hubble telescope or the very large array operating in New Mexico.

ALMA achieves its exceptional resolution and sensitivity by linking all of the 64 antennas into an interferometer array. In this setup, the exact instant at which a radio wave reaches each of the antennas is precisely recorded. Since the relative position of each antenna is well known, the source of the wave can be accurately pinpointed by comparing the timing (or phase) of the wave arriving at any one antenna relative to the other antennas using real-time correlator systems. The distance between two antennas is known as the baseline. A large baseline causes signals to arrive at the antennas with a large differential delay, and thus accurate angular resolution can be achieved. The ALMA antennas can be moved into different configurations like chess pieces using a specially designed truck to achieve different combinations of resolution and sensitivity. The maximum resolution is obtained with baselines up to 18 km.

To accurately measure the phase of the sky signal over the entire array or subarray, every antenna must receive a highly stable common reference signal known as the local oscillator (LO) reference. For ALMA, this LO reference signal is composed of two optical waves sent through a single optical fiber [2]. Both waves have a wavelength around 1.556 µm to allow transmission through conventional telecommunication optical fiber with little loss. One optical wave is generated by a master laser (ML), while the other is generated by phase-locking a slave laser at a given frequency offset from the master. Both

![Figure 1](Image)
lasers are located in a central building (see Figure 2). The frequency offset between the two lasers ranges from 27–142 GHz.

At each antenna, the photonic LO reference signal is sent to a photodetector, which acts much like a conventional RF mixer but at optical frequencies. The output of the photodetector therefore contains an RF beat note signal at the frequency difference between the ML and slave lasers, that is, the original 27–142 GHz offset frequency. This LO reference signal is used to phase-lock the antenna oscillators whose outputs are converted to 27–938 GHz LO signals using cryogenically cooled frequency multipliers [2], [3]. The LO signal is then used to downconvert the sky signals to an intermediate frequency (IF) band of 4–12 GHz. This IF signal is digitized and sent back to the correlators in the central building for processing to extract the phase information and ultimately generate astronomical images.

One critical requirement for ALMA is that the timing of the LO reference signal arriving at any antenna must be stable within 38 fs (1 femtosecond = 10^{-15} s). Larger timing fluctuations would degrade the accuracy with which the signal source can be pinpointed and would consequently result in a blurred image, reducing the scientific value of the data. To better understand the implication of this specification, it is useful to consider that a signal propagating at the speed of light travels only 1 µm in 3 fs. Maintaining a propagation delay stable within a few tens of femtoseconds implies that the length of the fiber used to transmit the LO reference signal must be stabilized to within a few micrometers, even though the path length may be as great as 18 km. Optical and electronic components used in conventional open-loop designs generally cannot provide such stability. The thermal expansion of the fiber caused by diurnal cycles can create effective fiber-length fluctuations that far exceed allowable values. Additional stretching of the fiber that runs up the antenna may occur when the antenna rotates. Therefore, a technique for dynamically stabilizing the fiber length is needed.

**FIGURE 2** The photonic local oscillator reference distribution system. The optical wave from a single master and phase-locked slave lasers are combined in a multikilometer optical fiber and sent to each antenna to generate the 27–142 GHz reference signal by photomixing. Each LLC subsystem measures the round-trip length of a fiber using interferometric methods to stabilize the length of fiber to the antenna to within a few micrometers, ensuring accurate timing of the reference signal.
This article provides an overview of three critical ALMA subsystems that allow the optical distribution of a low-noise LO reference signal to the antennas with the required stability. These subsystems are the laser synthesizer (LS), the line length corrector (LLC), and the ML. The LS phase-locks a slave laser optical signal to an ML to generate an extremely pure beat note used as a reference signal, which can be distributed to the antennas through optical fibers. The LLC system controls the length of the fibers to ensure that the propagation delay of the reference signals to the antenna is constant. Finally, the ML stabilizes the optical frequency using an atomic gas reference to provide an accurate reference to perform the line length correction.

THE LASER SYNTHESIZER

A laser can be thought of as a noisy oscillator whose output is not an ideal sinusoidal wave but rather a sinewave corrupted with intensity and phase noise modeled by

\[ E(t) = A(t) \cos(2\pi f_t t + \phi(t)), \]

where \( E(t) \) is the amplitude of the electrical field of the optical wave, \( A(t) \) is the amplitude noise, \( f_t \) is the average optical frequency of the wave, and \( \phi(t) \) is the phase noise. Sending two laser beams onto a photodetector generates the beat signal

\[ i_{\text{beat}}(t) = A_1(t)A_2(t)\cos(2\pi(f_1 - f_2)t + \phi_1(t) - \phi_2(t)). \]

Indices 1 and 2 distinguish individual lasers. Assuming that the intensity noise of the laser is negligible, the remaining noise that the beat note receives at the antenna is the difference \( \phi_1(t) - \phi_2(t) \) between the phase noise between the ML and slave lasers. If not compensated, this phase noise is transferred to the LO frequency, degrading the array coherence and visibility. Since the phase noise of a laser is orders of magnitude larger than that of typical RF oscillators, the beat note between two free-running lasers is completely unusable as a LO reference source. The role of the LS is thus to implement a locking loop that dynamically corrects the optical phase of the slave laser so that the slave laser accurately tracks the phase noise of the ML. This process is known as an optical phase lock loop (OPLL). Since the two lasers become highly phase correlated, the phase noise cancels out on the RF beat note generated at the antenna; consequently, an extremely pure reference signal is obtained. This reference signal can then be used to generate the LO signals with frequencies up to 938 GHz.

It might seem impossible to develop an electronic feedback system that controls the phase of an optical wave with a wavelength of 1.556 \( \mu \)m, or equivalently, an optical frequency of 192.6 THz (1 terahertz = 10^{12} Hz). However, although the optical frequency is high, the phase fluctuations of some types of lasers, such as fiber lasers, occur mostly at low frequencies and thus can be compensated electronically.

Figure 3 shows a block diagram of the baseline design of the ALMA laser synthesizer, which phase-locks the slave laser to the ML at an offset frequency specified by an RF synthesizer. In this system, the noisy beat note from the two lasers is detected with a photodetector. The resulting noisy 27–142 GHz beat note is compared to a pure RF signal generated by a high-quality frequency synthesizer by mixing both signals in an electrical mixer to produce a phase error signal. The mixer output would be a constant voltage if the beat note between both lasers perfectly tracked the wave provided by the RF synthesizer. Conversely, any phase drift would cause a voltage variation. This phase error signal is fed back to the slave laser so as to alter the phase of its optical output to track the optical phase of the ML. The frequency offset between the ML and slave lasers is determined by the RF synthesizer frequency.

![Figure 3](image-url)

**Figure 3** The laser synthesizer implemented using an optical phase-locked loop technique. The light from the master laser is mixed with that of the slave laser on a high-speed photodetector to generate an RF signal from 27–142 GHz. This signal is compared with the output of an RF synthesizer with a harmonic mixer to generate a phase error signal, which is used to phase-lock the optical wave of the slave laser to the master. The rapid phase corrections are done by an optical frequency shifter [acousto-optic modulator (AOM)]. The remaining frequency corrections are performed by a piezo transducer that stretches the fiber laser grating. Once phase locked, the beat note between the phase-correlated master lasers and slave lasers becomes a very pure beat note. A controller ensures automatic locking and monitoring of the subsystem.
Computation of the Required Loop Bandwidth

The required locking bandwidth of the OPLL is computed by measuring the power spectral density (PSD) $S_{\theta}(f) + S_{\phi}(f)$ of the combined phase noise of the ML and slave lasers and applying the transfer function corresponding to the closed-loop response $H_{PLL}(f)$ of the error signal relative to input perturbations. In this case, the OPLL acts as a highpass filter. Low-frequency phase fluctuations are thus tracked almost perfectly, whereas fluctuations outside the locking bandwidth remain largely unaffected. The total residual phase noise power $\theta^2$, which is obtained by integrating the filtered phase noise, is given by

$$\theta^2 = \int_{-\infty}^{\infty} (S_{\theta}(f) + S_{\phi}(f))|H_{PLL}(f)|^2 df.$$

The OPLL cutoff frequency necessary for meeting a given phase noise level can therefore be estimated using a first-order, highpass filter. In the case of fiber lasers, a bandwidth on the order of 1 MHz is needed to meet the ALMA phase-noise specification of $2.1 \times 10^{-5}$ rad$^2$ for a beat note of 27 GHz.

Optical Phase Control Mechanisms

To provide actuation for closed-loop control, a mechanism for changing the optical phase of the slave laser is needed with a bandwidth of at least 1 MHz. One mechanism uses the tuning of the frequency of the fiber. This tuning is achieved by applying a voltage to a piezo crystal, which stretches the Bragg grating that constitutes the lasing cavity. Increasing the frequency of the optical wave causes the optical wave of the slave laser to oscillate more rapidly. Consequently, the phase of the optical wave increases more rapidly with time as longer as the higher frequency is maintained. The locking loop can therefore increase the frequency of the slave laser until its optical phase catches up with the phase of the ML. The opposite scenario applies with decreases in the slave laser frequency. The loop designer must account for the fact that the phase correction is cumulative over time. In other words, the phase correction corresponds to the integral of the frequency correction. This implicit integration creates a pole at the origin and, thus, a 90° phase shift in the open-loop transfer function of the system.

Unfortunately, the laser tuning mechanism is mechanical in nature and displays lightly damped mechanical resonances above 20 kHz. These resonances introduce phase lags that prevent high loop bandwidth. To circumvent this problem, an additional external optical frequency shifter (acousto-optic modulator) is used to apply small but fast frequency changes to the laser output with a bandwidth of up to 1 MHz. The feedback network circuit of the OPLL is split into two parallel branches with the fast frequency shifter handling the high-frequency, low-amplitude compensation. The remaining low-frequency phase error is cancelled by a second feedback network circuit driving the laser piezo.

Automation of the Phase Locking

The phase-locking control system is based on analog electronics to achieve high accuracy and high bandwidth. The locking loop, however, must be accompanied by a digital control system to initiate the locking sequence in the proper order. The LS includes an embedded computer that receives frequency tuning requests from the ALMA central controller through a CANBus link. The controller then sets the RF frequency synthesizer to the appropriate frequency offset and tunes the slave laser until the frequency difference between the ML and slave lasers is close enough to be within the phase-locking range. The controller then enables the locking loop and signals the central controller that the tuning is successful.

Optical Phase-Locking Results

Preliminary implementation of the fiber laser-based LS with the dual feedback loop demonstrates that delay fluctuations of 34 fs RMS (integrated from 3 kHz to 3 MHz) can be achieved for a beat note of 108 GHz [4]. This delay noise corresponds to a phase noise of $3.3 \times 10^{-5}$ rad$^2$ at 27 GHz, which is close to the specification. Improvements of the loop bandwidth will allow the phase noise to meet the specification.

THE LINE LENGTH CORRECTOR

The line length correction (LLC) system is another specialized control loop that is essential to the high-accuracy operation of ALMA. The LLC ensures that the length of fiber connecting the central building to the antenna is stable to within a fraction of a micrometer by sensing the optical length of the fiber. This sensing is achieved by using the entire length of the fiber to form an optical interferometer (see Figure 4). The light of the ML (along with the slave laser) is sent to every antenna and returned to the central building along the same fiber after passing twice through a 25-MHz optical frequency shifter. The returned ML light is therefore offset by 50 MHz. The phase of the returned optical wave is affected by variations in the length of the fiber. Indeed, the optical wave shifts by $2\pi$ every time the fiber roundtrip length changes by one wavelength, that is, 1.5 $\mu$m. This phase shift is measured by mixing the original ML light with the returned signal on a photodetector, resulting in a 50-MHz beat note whose phase also changes by $2\pi$ for every wavelength change. This optical interferometer therefore provides an extremely sensitive measurement of changes to the fiber length. The phase of this RF signal is measured by mixing the beat note with a stable 50-MHz reference signal. The mixer output varies as the cosine of the phase difference between the beat note and the reference signal. The role of the locking loop is to correct the length of the fiber to maintain the phase difference at a fixed value and, therefore, ensure that the length of fiber is stabilized to within a fraction of a wavelength.

Fiber Length Control Mechanisms

The length correction of the fiber is implemented using fiber stretchers, which consist of a length of fiber attached to a piezo transducer in such a way that a change in voltage to the piezo changes the mechanical tension applied to the fiber. To obtain fast tuning of the fiber length, a short length of fiber is
used with a small piezo to minimize the total inertia, yet the correction range is small. On the other hand, using a long fiber rolled on a cylindrical piezo allows large but slow length corrections. Since ALMA requires corrections up to a few millimeters over a bandwidth of many hundreds of hertz, it is necessary to use both types of stretchers and design the feedback control to generate appropriate correction signals for each stretcher.

In the current implementation of the feedback control, the error signal from the mixer is passed through a proportional-integral-derivative (PID) compensator to generate a high-bandwidth correction signal that is sent to the fast stretcher. This correction signal is also supplied to another PID compensator controlling the slow stretcher, forming a second loop that is designed to regulate the correction signal to zero. This cascaded loop configuration ensures that the slow stretcher handles the large corrections so that the fast stretcher does not reach its limit and saturate. The control parameters must be tuned to account for the mechanical resonances of the stretchers. The gain of each loop must be set so that phase lags introduced by each individual loop do not destabilize the global feedback system.

The maximum bandwidth of the LLC is limited by the roundtrip propagation delay of the light in the fiber between the central building and the antenna. With a fiber length of 15 km, the effect of a correction to the fiber length can be detected only after 150 \( \mu s \). This delay substantially decreases the phase margin of the loop, limiting the possible bandwidth to about 1 kHz.

Another interesting aspect of the LLC locking loop is that the error signal is a periodic function of fiber length. A large and fast length perturbation due to a mechanical stress in the fiber may cause the error signal to skip an entire cycle. If the locking loop is unable to react quickly enough, the locking loop will settle on another fringe and the LO reference will experience a phase step at the antenna. This situation is known as cycle slip. Work is underway to estimate the probability of such slips and their effect on the overall system. Variations of the LLC architecture have also been explored to address the cycle-slip problem [5], [6].

**Line Length Correction Results**

Figure 5 shows the measured delay drift (expressed in terms of phase shift) of an 80-GHz beat note going through 5 km of optical fiber, with LLC turned on and off [7]. The RMS phase fluctuations measured over a 10-s time interval is 0.22°, which corresponds to 33 fs. This value is acceptable for the application. The correction voltage to the fast fiber stretcher is also shown. This test uses a cascade of two commercially available piezo fiber stretchers as described above. The first has a stroke of about 25 \( \mu m \) and bandwidth of 1 kHz, and the second has a stroke of 5 mm and a bandwidth of a few hertz.
THE MASTER LASER

The interferometric measurement of the fiber length performed by the LLC uses the optical beam originating in the ML as a reference. This measurement method imposes two important requirements on the ML. First, the coherence length of the ML must be sufficiently long (>30 km in fiber) to ensure that the measured interference fringes are well-defined, enabling accurate line-length stabilization with a low probability of cycle slip. Second, the optical frequency of the ML must possess a relative frequency stability that is better than the required relative fiber length accuracy. This frequency stability is necessary because the ML optical frequency is the reference by which the fiber length is measured. Indeed, to stabilize 15 km of fiber within 1 μm, a relative optical frequency stability better than 6 × 10⁻¹¹ (1 μm/15 km) is necessary. Since the optical frequency of the ML is around 192.6 THz (1,556.2 nm), this degree of stability corresponds to optical frequency fluctuations less than 12 kHz (192.6 THz × 6 × 10⁻¹¹).

The Laser Source

A 1,556-nm distributed feedback (DFB) fiber laser is used as the source for the ML since such a laser provides a compact and robust device with a narrow linewidth and, therefore, a long coherence length [8]. Furthermore, DFB fiber lasers can provide high optical output power levels (up to 90 mW) with an acceptable level of intensity noise. These lasers therefore meet the coherence requirement. However, the frequency stability of such lasers is insufficient for the LLC system since their frequency can fluctuate by tens of MHz as a function of ambient temperature and time. For this reason, the frequency of the laser needs to be compared to a stable optical reference, and a control loop must compensate the optical frequency fluctuations.

The Optical Reference

The optical reference selected for the ML is a transparent cell containing low-pressure gas of rubidium (Rb) atoms. Rb has the property that when a 778-nm (red) laser beam with the exact right frequency passes through the gas, a faint 420-nm (blue) fluorescence signal is emitted by the excited Rb atoms. The phenomenon is known as the two-photon transition of Rb. This blue light can be detected with a photomultiplier tube. Since this two-photon transition is highly stable and occurs only in a narrow band of optical frequencies (theoretically less than 200 kHz at 1,556 nm), the transition can be used as a sensitive frequency discriminator signal to which the laser can be locked to improve its frequency stability.
Figure 6 illustrates how the first prototype of the ML is frequency-locked to the two-photon transition of Rb. First, part of the 1,556-nm DFB fiber laser output is converted into 778-nm light by using an optical frequency doubler. The frequency doubling is performed by a periodically poled lithium niobate (PPLN) crystal, which is an optically nonlinear element. The efficiency of the frequency doubling depends on the quasi-phase matching of the 778- and 1,556-nm waveforms in the polled structure in the waveguide. For this reason, the frequency doubler is installed in an oven that maintains the crystal at a fixed temperature (77.4 °C). However, perfectly accurate temperature regulation of the crystal is not possible, and thus its temperature is affected by external temperature changes. The temperature setpoint of the oven is therefore continuously optimized by the ML controller using a slow locking loop algorithm implemented in software. This algorithm compensates for the effects of ambient temperature changes by seeking the doubler temperature setting that provides the highest output power.

The 778-nm light is then sent through the Rb cell and reflected back on itself to stimulate the two-photon transition of Rb. The resulting counterpropagating beams eliminate the linewidth broadening caused by the Doppler shift due to the Rb atoms moving randomly and rapidly in the cell. The temperature of the gas cell is maintained to about 100 °C by a conventional analog temperature servo loop to vaporize Rb atoms to fill the gas cell.

The Frequency Control Loop
To facilitate laser locking at the frequency where fluorescence is maximum, the 778-nm beam is phase modulated using an electro-optic modulator (EOM). This phase modulation creates a sideband of opposite phase on each side of the optical carrier. If the optical frequency of the laser is on the center of the symmetrical two-photon transition, both sidebands are absorbed equally by the narrow linewidth, cancelling out completely. This modulation is therefore not visible on the fluorescence. If the laser drifts away from the center of the resonance, the two carriers do not cancel completely and a modulation at the phase modulation frequency is detected. The phase of this modulation indicates on which side of the resonance the frequency of the laser has drifted. The synchronous detection extracts the amplitude and phase information from the fluorescence signal. This information is used as a frequency error signal to indicate the frequency offset of the laser relative to the center of the resonance.

The error signal is sent to an integral controller (a Stanford Research model SIM960), and the resulting compensation signal is used to tune the laser to regulate its frequency to that of the two-photon transition. As with the slave laser, frequency tuning is achieved by stretching the laser’s Bragg grating with a piezoelectric transducer (PZT). The PZT can tune the laser frequency by 7.4 MHz/V over an operating range of 0–200 V, yielding a total adjustment range of 1.5 GHz.

The selection of a loop gain, and therefore the locking bandwidth, must compromise between the robustness of the frequency locking and the phase noise on the ML. The error signal is noisy since it is obtained by photomultiplication of a weak fluorescence. The use of a synchronous detector and an integral controller reduces this noise. However, the residual electronic noise passed to the laser frequency tuning signal is a source of optical phase noise on the laser output. Since the laser tuning is highly sensitive, even a small amount of noise can destroy the coherence length of the laser, rendering the laser unusable by the LLC system. Although a high loop gain in the frequency control loop provides a high locking bandwidth, the resulting phase noise is large. Thus, the gain of the integral controller, and consequently the bandwidth of the locking loop, must be limited. A locking bandwidth of a few tens of hertz was found to provide the best trade-off between locking robustness and phase noise for the ML prototype.

![Figure 7](image-url)
Automation of the Frequency Locking

An embedded controller plays the crucial role of automating the locking of the ML on the desired two-photon transition of Rb. Upon powerup, it is not possible to tune the laser with sufficient accuracy to place its frequency within the locking range of the desired transition. To solve this problem, the ML embedded software implements an automatic frequency calibration and locking algorithm. The algorithm first stabilizes the temperature of the components of the system (frequency doubler, Rb cell, and laser) and then sweeps the laser frequency using the PZT voltage while recording the fluorescence signal until the pattern corresponding to the desired Rb transitions is found. If the transitions are not found, the laser is tuned to another frequency range by changing the laser temperature. Once the correct transition is found, the frequency of the laser is adjusted close to the targeted value and the locking loop is activated. The software regularly monitors the various system signals, such as fluorescence level, frequency doubler output power, and cell temperature, to detect possible problems and adjusts control signals to compensate for slow parameter drift.

Frequency-Locking Results

The absolute frequency of the optical wave generated by the frequency-locked ML is 192.6425712 THz. The frequency stability of the performance of the laser is measured by beating the output of the ML with the output of a reference laser and measuring the resulting beat frequency as a function of time. The effect of the frequency stabilization can be seen in Figure 7. The measured relative frequency stability expressed as the Allan standard deviation is $2 \times 10^{-12}$ over time scales of 1 s, and $5 \times 10^{-12}$ over times scales of up to 300 s. These results demonstrate that the ML can be operated with stability levels that exceed the ALMA requirements.

CONCLUSIONS

This article discusses three important subsystems of the photonic LO reference distribution system for the ALMA radiotelescope. Each subsystem relies on specific control systems that allow ordinary components to be assembled to form a global system that is more accurate and stable than its individual components. By using appropriately designed loops, lasers with phase noise of many thousands of rad$^2$ were phase-locked to generate high-purity microwave signals with phase noise below $3.3 \times 10^{-5}$ rad$^2$ at 27 GHz, fibers with lengths fluctuating by more than a few millimeters were compensated within a fraction of a micrometer, and optical frequencies of lasers normally fluctuating by tens of megahertz were stabilized to within a few kilohertz. These examples demonstrate how control systems can be used with photonic and electronic systems to achieve remarkable results.

Of course, ALMA is built around many more control systems and feedback loops than those presented here, such as the LO phase-lock loops and antenna-positioning systems. Work is currently under way to optimize and test these systems. The first operational antennas will be installed in Chile in 2007, and the full array will be completed by 2011. Once fully operational, the ALMA radiotelescope will deliver scientific results that will provide a new understanding of our universe by making apparent what was invisible to previous instruments.

AUTHOR INFORMATION

Jean-François Cliche (jfcliche@teraxion.com) received his B.S. and Ph.D. degrees in electrical engineering from Laval University, Québec, Canada, in 1993 and 1999, respectively. In 2000, he worked at Rutherford Appleton Laboratory, Didcot, U.K., on the development of high-performance data acquisition systems for particle physics experiments. He is a cofounder of DiCOS Technology (now part of Teraxion Inc.), where he supervises the development of high-performance frequency-stabilized laser sources for various applications. He is in charge of the development of photonic solutions for the Atacama Large Millimeter Array (ALMA) radiotelescope, including the master and slave lasers for the photonic local oscillator reference. He is a Member of the IEEE and a professional engineer registered with the Order of Québec Engineers (OIQ).

Bill Shillue received the B.S. degree in electrical engineering from Cornell University in 1985 and an M.S. degree in electrical engineering from the University of Massachusetts in 1990. In 1991, he joined the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia, and participated in the design and deployment of a 13.7-m satellite earth station in support of the NASA Orbiting-Very-Long-Baseline-Interferometer Project. In 1994, he joined the NRAO in Tucson, Arizona, and developed millimeter-wave receivers and instrumentation for the 12-m telescope. In 1998, he began work on the Atacama Large Millimeter Array, developing key photonic technologies for local oscillator generation and distribution. He is a Member of the IEEE Lasers and Electro-Optics Society, the IEEE Antennas and Propagation Society, and the IEEE Microwave Theory and Techniques Society.

REFERENCES