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Sound Alerter Powered Over an Optical Fiber

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An optically powered sound alerter has been constructed which demonstrates the feasibility of converting optical power into sound power with good efficiency and at power levels comparable to those of present telephone ringers. The alerter has an overall optical-to-acoustic efficiency of about 35 percent at 2 mW of acoustic output power. Optical power is converted to electrical power by a 52-percent efficient photovoltaic detector and then into acoustical power by a 72-percent efficient electroacoustic tone generator which uses a piezoelectric transducer. This demonstration establishes that it is technically feasible to deliver optically, via a fiber lightguide, sufficient power to operate a telephone, since all other telephone signaling functions can be accomplished, in principle, with less power and within the context of dielectric lightguide technology. For conventional usage, the design of a telephone alerter must take many factors into consideration, including background noise masking, frequencies not irritating to the customer, satisfactory performance for customers with impaired hearing, etc. These factors have not been addressed here.

I. INTRODUCTION

The potential introduction of lightguide connecting residential and commercial premises to central switching offices offers exciting possibilities for communications users. The availability to each customer of hundreds of megahertz of inexpensive switchable bandwidth could revolutionize telecommunications. One cost barrier to the employment of lightguide in the local loop would be eased if the guide could also be used to provide the essential functions of ordinary telephone service without requiring metallic wires to carry electrical power to the telephone. The possibility would then exist for introducing a lightguide telephone system; the essential functions of this system would be powered from central offices, and broadband services could subsequently be added to it in a cost-effective manner. The broadband services and non-essential telephone services could be locally powered.

The largest technical uncertainty limiting the consideration of dielectric lightguide for ordinary telephony is power: Can telephone operating power requirements realistically be met by photovoltaic conversion of optical power emergent from the lightguide? Since the largest power demands in a conventional telephone occur when the bell is rung, we have given first priority to investigating the power efficiency of an optically driven sound alerter. The other essential functions—speech signaling and recognition of the telephone hook status—will be discussed in a subsequent report.

II. AN OPTICALLY POWERED ALERTER

Electromechanical ringers of the *TRIMLINE*® and 500D-type telephones produce multitone outputs in the range from 0.4 to 0.6 mW of acoustic power; the simultaneous sounding of five ringers (extension telephones) produces 2.5 mW of acoustic power; and the S1A "hard-of-hearing" alerter produces 4 mW of acoustic power. Cost, physical size, and customer acceptability of the alerter noise are important features in the design of these ringers and in the past have dominated the economic importance of high electroacoustic efficiency. However, if the acoustic power levels just listed are to be realized (or even approached) with optically powered sound alerters, then the attainment of high optical-to-acoustic power conversion efficiency is a matter of paramount necessity—at least within the boundaries set by present laser and lightguide technology.

We have fabricated an optical sound alerter demonstration unit, shown in the photograph of Fig. 1 and block diagram of Fig. 2, in which optical power from a GaAlAs laser is transmitted through a large numerical aperture, low-loss, optical fiber and is air-coupled into a GaAlAs photovoltaic detector[1] where it generates dc electrical power at 1.0 volt. This is converted by attendant circuitry into an audio frequency waveform at the terminals of an electroacoustic tone generator which uses a piezoelectric transducer. The components are mounted on a 16-in. × 10-in. × 1/4-in. Lucite board with compact *X*-*Y*-*Z* positioners used for optical alignments. The 0.823-in. high × 1.156-in. diameter Helmholtz acoustic cavity was constructed as an integral part of the board, with the tone generator acoustic output coupled into the surroundings via a Helmholtz air piston consisting of 97 holes of 0.078-in. diameter drilled through the 1/4-in. Lucite thickness. A surface-tension microlens, formed by wetting the cut end of the optical fiber with a small drop of optical cement and curing in ultraviolet light, increased the laser-to-fiber coupling efficiency from 45 to over 60 percent. The photovoltaic detector quantum efficiency was improved by applying a thin-film, ZrO_2, antireflection coating which reduced the net reflection loss to 2.5 percent.

To simulate conventional telephone ringing, the laser transmitter is operated in a 2-second-ON, 3-second-OFF cycle (but is otherwise un-

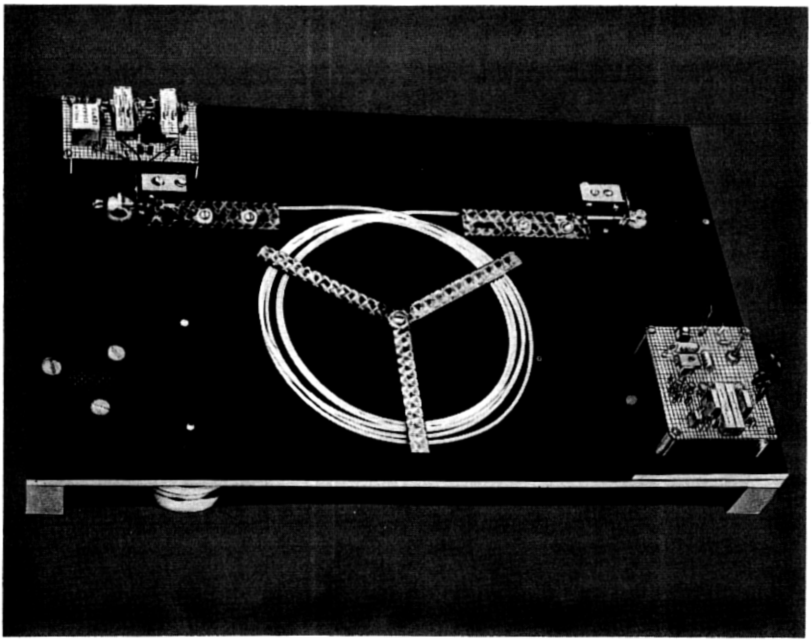


Fig. 1—Optically power sound alerter demonstration unit. Laser, on the right, is coupled by large N.A. fiber lightguide to the photovoltaic detector. Tone generator and high-Q inductors for the ringing choke circuit are at lower left.

modulated), causing the alerter to respond similarly. These periodic bursts of optical power are converted into electrical power by the photodetector, and this power is converted into an audio signal by a free-running, 2.0-kHz nominal frequency, astable multivibrator and an acoustically damped, ringing-choke circuit whose capacitive element is the tone generator. A portion of the acoustic response curve of the tone generator at room temperature is shown in the inset of Fig. 2. A raucous, buzzer-like sound is produced by a second multivibrator which sweeps the audio frequency over a ±100 Hz interval about 1.98 kHz at a 30-Hz rate. The ringing-choke and frequency-control circuits are operated directly from the photovoltaic detector output terminals.

Selection of the 2-kHz tone generator was based on measured comparisons of its acoustic output power with that of similarly designed 1.0-kHz and 1.4-kHz tone generators, the results being qualitatively consistent with acoustic efficiency scaling laws. The ±100-Hz frequency modulation ameliorates some of the more irritating effects associated with the use of a single, unmodulated tone—e.g., strong standing waves (and hence dead zones) in a room, an intensely piercing sound, and masking of the alerter sound if the noise environment contains pure tones of similar frequency. The expedient adopted for this demonstration is

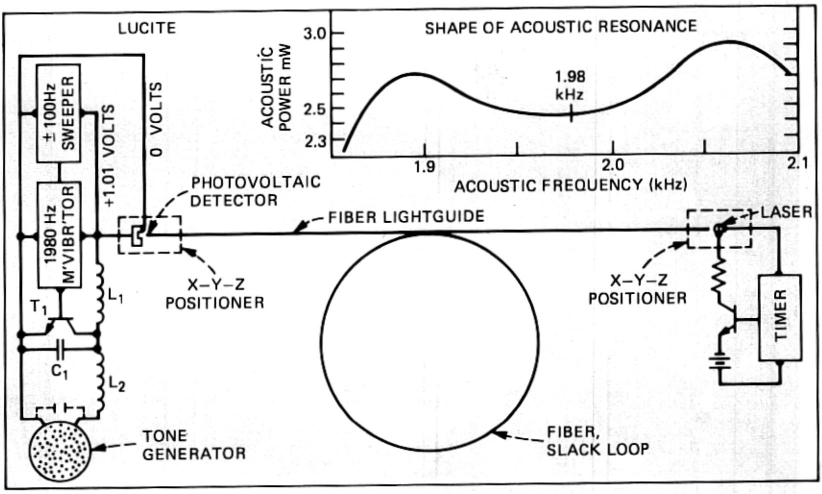


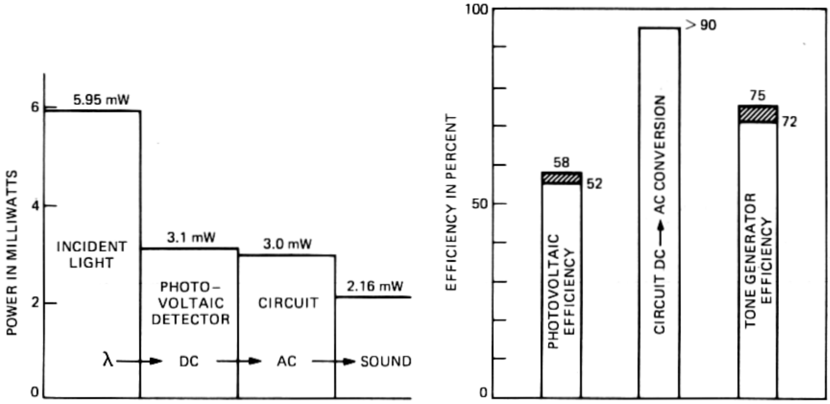
Fig. 2—Schematic of sound alert demonstrator. Laser is battery-operated, with a timing circuit controlling the 2-second-ON, 3-second-OFF ringing cycle. Optical acoustic efficiency was measured with the ±100-Hz sweeper disconnected and the optical fiber replaced by lenses. A 45F transistor is used for T_1. The values of L_1, L_2, and C_1 are 0.24h, 0.16h, and 0.0033 μf for 1.98-kHz operation. The tone generator room temperature acoustic output power at 5.0 V rms is shown in the inset for a limited frequency range.

a departure from usage in existing multitone telephone ringers, which incorporate widely spaced frequencies in the range 750 to 1600 Hz to satisfy human factors criteria. Our optical techniques can be extended to multitone systems with some loss in electroacoustic efficiency. It should also be noted that the volume occupied by the present tone generator and the high-Q inductors of the ringing choke circuit is larger than that consumed by conventional electromechanical telephone ringers.

III. EFFICIENCY

As seen from the Fig. 2 inset, the tone-generator output power varies by about ±5 percent over the ±100-Hz swept band. To obtain a definite, single-frequency result, the sound alerter optical-to-acoustical power conversion efficiency was measured at 1.98 kHz with the ±100-Hz sweeper disconnected. This sweeper consumes approximately 3 percent of the photovoltaic output power when used in the sound alerter demonstration unit. Accuracy in the efficiency measurements required that the optical fiber be replaced by a lens system which focused the $\lambda = 0.801$ μm laser output, with correction for astigmatism,[2,3] onto the photovoltaic detector. (Auxiliary measurements show that the fiber-to-detector coupling efficiency exceeds 95 percent.) Optical powers were measured with a thermopile whose calibration against a pyroelectric radiometer of ±0.5 percent absolute accuracy agreed to within ±1.1 percent with its standard lamp calibration. Acoustic powers were measured as functions of frequency and rms voltage in an absolutely calibrated anechoic test chamber. Electroacoustic efficiencies were obtained from this calibration and the voltage and current waveforms and phase angle at the tone generator.

A summary of the optical, electrical, and acoustic powers and power conversion efficiencies obtained in this measurement is given in Fig. 3. The overall efficiency, defined as the total sound power divided by the optical power incident onto the photovoltaic detector, achieves a maximum value in the range 33 to 36 percent at acoustic powers in the neighborhood of 2.1 mW. With our present unsophisticated circuits, the alerter efficiency decreases slowly and uniformly as the acoustic (or optical) power is lowered, and it decreases abruptly if the power is raised too high. This behavior follows from the shape of the photovoltaic V-I curve and from the fact that the ringing choke circuit presents a load at the detector output terminals which is nearly independent of optical power and which permits optimum photovoltaic efficiency to be achieved only over a narrow optical power range. Thus, the total acoustic power of 2.1 mW might be distributed among three or four alerters ringing simultaneously, but only if the present circuit were modified to maintain an optimum efficiency impedance match to the photodetector. Realization, in the present arrangement, of a previously attained "best" value of photovoltaic efficiency[1] could raise the overall efficiency into the 37 to 40 percent range.



(a) (b)

Fig. 3—Power and efficiency. (a) The indicated values represent optical power incident onto detector, detector dc output power, circuit audio frequency power into tone generator, and tone generator total radiated acoustic power at 1980 Hz. (b) The photovoltaic efficiency was 52 percent, and the tone generator efficiency was 72 percent for the results cited in this paper. A value of 58 percent has been measured on another detector of this type, and the present tone generator can provide 75 percent electroacoustic efficiency (over a narrower frequency band) by increasing its cavity height to 0.861 inch.

IV. EXTRAPOLATION TO FUTURE TECHNOLOGY A POWER ESTIMATE

The losses expected for the large N.A. fiber at the 0.801-μm wavelength used in the present demonstration alerter exceed 6 dB/km. Thus, even with perfect laser-to-fiber and fiber-to-detector coupling, at least 5 watts of optical power would be needed at the input end of a 5-km fiber to produce 5 mW of light at the photodetector, a large power indeed. However, fiber losses as low as 1.2 dB/km have been reported[4] at wavelengths near 0.9 μm, which are attainable with GaAs lasers and photodetectors, and as low as 0.5 dB/km at wavelengths near 1.3 μm, which are attainable with $In_xG_{1-x}As_yP_{1-y}$ devices.

For purposes of estimating the power that might eventually be needed at the central office to operate *one* optically driven sound alerter, we will consider the more optimistic case corresponding to 1.3-μm wavelength. In expectation that multi-junction[5] InGaAsP photovoltaic detectors can be constructed whose power conversion efficiency will be comparable to that of the present GaAs detector, we arrive at the values listed in Table I.

A 10-percent efficient InGaAsP laser driving a 5-km loop needs to draw only 0.10 watt during the alerter sounding (and considerably less during speech communication). For comparison, we note that present Bell-System-wired telephones draw at least 20 mA from a 50V battery, i.e., 1 watt, when operating, and they require more to ring.

The alerters on conventional extension telephones are rung simultaneously, but the correct engineering approach to ringing several optically powered telephones in one location is not obvious. A 1-second-ON, 2-second-OFF ringing sequence with appropriate circuits to switch between extensions would permit the ringing of three telephones with the same power as noted in Table I, provided the 2-second delay between

Table 1 — Central office power for $\lambda = 1.3\mu$m laser to operate one sound alerter

Assumed acoustic power per alerter	= 0.6 mW
Tone generator electroacoustic efficiency	= 75 percent*
DC-to-audio circuit efficiency	= 90 percent†
Photovoltaic power conversion efficiency	= 58 percent‡
Fiber-to-photodetector coupling efficiency	= 93 percent
Optical power required at fiber output end	= 1.65 mW
Fiber loss (N.A. = 0.2)	= 0.5 dB/km
Cabling losses (including splices)	= 0.8 dB/km
Total medium loss	= 1.3 dB/km
Laser-to-fiber coupling efficiency	= 80 percent
Optical power required at central office for fiber length of:	1 km 2.8 mW
	2 km 3.8 mW
	5 km 9.2 mW
	10 km 41.2 mW

* Present best value, near 2 kHz.

† Assumes that circuit load line is matched to photovoltaic optimum power point for the optical power actually used.

‡ Assumes that multi-junction photovoltaic efficiency can be made equal to single junction efficiency.

ringing the first and third telephones is tolerable. The ringing of more extensions and of a hard-of-hearing alerter would probably require the assistance of local power, as would additional services such as wideband video.

One reason for examining the possibilities of optical systems in the loop plant, in today's time frame, stems from the expanded services to telephone subscribers which are implicit in the hundreds of megahertz of switchable fiber bandwidth. Beyond this, there are many technical advantages, including freedom from lightning strikes (low voltage electronics), power line pick-up, and problems with potentially dangerous electrical pick-up from customer-provided electrical equipment. Optical loop systems would be more difficult to tap and thus somewhat more secure than wired systems. They may also exhibit compelling cost advantages and power savings, but today's technology is much too rudimentary to permit firm predictions.

V. SUMMARY

We have measured an optical-to-acoustic power conversion efficiency of 33 to 36 percent on an optically powered sound alerter driven by a 0.801-μm wavelength laser. Assuming that comparable efficiency can be attained in the 1.3-μm wavelength range of low fiber-lightguide losses, this result suggests that the optical powering of telephones over glass fibers may in the future be technically feasible for loop lengths up to at least 5 km—in the sense that the other essential station set signaling functions can be performed compatibly with an all-dielectric technology at less power than that consumed by the sound alerter.

Since the high efficiency is made possible by restricting the alerter acoustic output to a narrow range of high frequencies, the tone quality of optically driven alerters would not be expected to equal that of conventional electromechanical ringers. Also, it is unclear, with limited optical powers, how best to handle the problems of ringing extension telephones and hard-of-hearing alerters.

VI. ACKNOWLEDGMENTS

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