Alexander Graham Bell's PHOTOPHONE

In 1880, Alexander Graham Bell and his assistant, Sumner Tainter, unveiled a dramatic advance in optical communication technology, which they called "the photophone." Without the benefit of lasers or modern detectors, the photophone could transmit a human voice hundreds of meters on a beam of light. The photophone was the world's first electro-optical system, and Bell and Tainter's experiments preceded wireless voice communication by radio by at least 19 years.[1]

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EARLY OPTICAL COMMUNICATION

Today, the words "optical communication" usually evoke images of advanced fiber optic networks. However, a ray of light always communicates something to the person who sees it, and light has been exploited for sending messages since antiquity. For long distance communication, the ancient civilizations of China, Egypt, and Greece used smoke by day and fire by night to relay signals.[2] Among the earliest historical references to optical communication are those from the siege of Troy in 1084 BC. Most accounts acknowledge that a lamp or torch was used to signal the Greek army that the time was right to attack the city.[3] In his tragedy "Agamemnon," Aeschylus[4] gives a detailed account of a chain of signal fires lit on the summits of Mounts Ida, Cithaeron, Anthos, and others to transmit the news of the victory to Argos. Although the story of the siege of Troy is probably more myth than historical fact, it shows that the idea of sending messages over long distances by optical means has been around for at least 3,000 years.

One of the first optical communication systems in North America was established about 300 years ago in the colony of New France (present day Quebec).[5] Increasingly threatened by the possibility of naval attack by Britain, the government of New France established posts for signal fires at villages along the south bank of the St. Lawrence River. As described by Roy,[5] there were at least 13 sites in the chain starting at Ile Verte about 200 km down river from Quebec City. Beginning in the early 1700s, a guard was posted at each village every night during the navigation season to watch for any signal from the next village down river. After nightfall, it took about two hours to relay a warning to Quebec City that enemy ships were approaching.

In the spring of 1759, the British began the offensive that led to the fall of Quebec on Sept. 13, 1759. The approach of the British navy was communicated to Quebec City by the chain of signal fires. British Lieutenant John Knox, on board the "Good Will," recorded in his journal on June 19, "We see large signal fires everywhere before us..." Records show that the fires were lit every night to report the progress of the enemy up the St. Lawrence River toward Quebec City.

One of the first advances in optical communication was the Chappe semaphore, used in the early 1800s. In this system, towers were erected at the tops of hills at intervals of 5-10 km. At the top of each tower was a system of movable wooden arms whose positions denoted various phrases, numbers, and the letters of the alphabet. In principle, any message could be relayed from tower to tower, given enough time. Data was transmitted at the rate of one signal per minute. Although this seems slow, a message could be transmitted over long distances much more quickly than the fastest alternative—a messenger on horseback. There were several semaphore networks linking major European cities, including a string of 220 towers from the Prussian border via Warsaw to Leningrad that employed 1,300 operators.[6] The Chappe semaphore was the state-of-the-art in optical communication when Bell had the inspiration for the photophone.

DEVELOPMENT OF THE PHOTOPHONE

In July 1877, Bell married Mabel Hubbard and the newlyweds set off on an eighteen month honeymoon in England. During the trip, Bell gave public lectures to promote his telephone, which was patented just the year before. Bell was

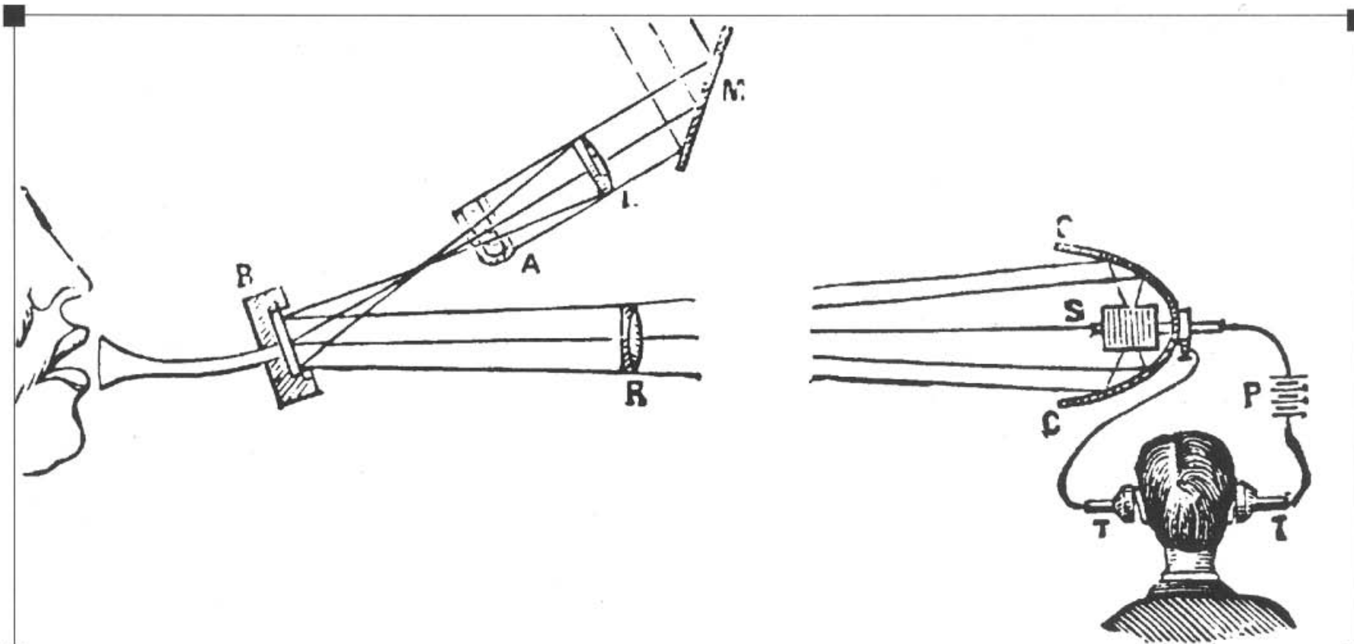

Figure 1. "Theoretical diagram of the articulating photophone." A mirror, M, reflects a beam of sunlight through a lens, L, and a cell, A, containing alum water, which absorbs heat from the sunlight that could damage the transmitter, B. The transmitter is composed of a thin glass disk, silvered on one side. The disk becomes alternately concave or convex in response to the vibrations of the speaker's voice so that the divergence of the reflected beam is modulated. The second lens, R, collimates the beam for projection to the receiver. At the receiver, a parabolic mirror C, concentrates the beam on the selenium cell, S, which is in series with a battery, P, and a pair of telephone earpieces, T. The resistance of the selenium varies according to the intensity of the received light so that the listener perceives the voice of the distant speaker. This sketch first appeared in "Bell's Photophone," *Scientific American* **36:1**, January 1881. Can you spot the error in it?

already thinking about ways to improve the telephone. He recognized that a weakness of the telephone described in the patent was that its magneto-inductive transmitter would never be practical for long distance communication. A variable resistance transmitter would have to be developed that could modulate large currents for long distance applications. This must have been frustrating for Bell, since his first successful demonstration of the telephone actually used a type of variable resistance transmitter.[7] Unfortunately for Bell, before he even returned from his honeymoon, Thomas Edison applied for a patent for the variable resistance carbon button transmitter in February 1878. Variations on Edison's transmitter became a standard component of telephones for the next 75 years.

Meanwhile, articles had been published in the scientific literature about the curious properties of the element selenium. Willoughby Smith reported that the resistance of bars of selenium was affected by light,[8] and Werner Siemens had constructed an effective optical detector from selenium that had a resistance 10 times less in sunlight than in the dark.[9] Bell followed these developments closely. It was natural for him to wonder how the variable resistance properties of selenium could be applied to the telephone, and he may also have seen in selenium an opportunity to out-do Edison and his carbon transmitter. During a speech before the Royal Institution on May 17, 1878, he revealed the principal idea of the photophone: "If you insert selenium in the telephone battery and throw light upon it, you change its resistance and vary the strength of the current you have sent to the telephone, so that you can hear a shadow."[10]

Bell returned to the U.S. in November 1878 with a sample of selenium, but initial experiments showed that the resistance of the selenium was far too high "for the experiment of hearing light."[10] Investigations had to be postponed for the next year as Bell was consumed by the Dowd telephone infringement case. By October 1879, the Dowd case was drawing to a close in favor of the Bell Telephone Co., and Bell was ready to pursue the photophone idea in earnest. He hired Tainter, a 25-year old instrument maker, for $15 a week and an interest in any joint inventions. A laboratory was set up in a rented house on L Street in Washington, D.C.

Development of the photophone soon became a mission for Bell and Tainter. On Jan. 22, 1880, they recorded in their notes, "...we are both so fascinated by the scientific prospects opened up that we have determined to make the electric photophone our great object of search."[10] Their emotional commitment was evident in notes made in early February after some unsuccessful experiments: "The failure of the experiments produced so great a reaction that we have both been quite unwell ever since."[10]

Two major problems had to be addressed in their photophone investigations. For the receiver, the problem was to produce, using selenium, a detector of sufficiently low resistance that it could function in series with a telephone earpiece. They finally came up with a composite detector composed of concentric ring shaped selenium cells connected in parallel. The composite detector had a resistance of 300 ohms in the dark and 155 ohms "in the light."[11]

For the transmitter, the problem was how to modulate the intensity of a light beam in accordance with the vibrations of the speaker's voice. Bell's notes show dozens of ideas for the modulator, including a gas lens in which the pressure waves of the speaker's voice change the curvature of a pair of membranes containing a gas with a refractive index greater than that of air.[12] Although Bell and Tainter did not have much luck with their gas lens, the ducting of light through a tubular gas lens was explored in the 1960s at Bell Labs.[13] Another idea was to use the current produced by a variable resistance telephone to induce a magnetic field inside a solenoid in which there was a cell containing carbon disulfide. This material has a high Verdet constant and rotates the plane of polarization of light in the presence of a magnetic field. With crossed polarizers on both sides of the cell, the intensity of a light beam could be modulated by the Faraday effect.[14]

The first successful photophonic transmission was achieved using a "double grating" modulator. In this device, a grating ruled on a silver coated glass plate was attached to a diaphragm. A second grating was fixed a few millimeters away. The voice of someone speaking near the diaphragm caused the first grating to vibrate, thus varying the amount of light that could pass through the pair of gratings.[15] On Thursday, Feb. 19, 1880, a selenium cell was placed a few centimeters behind the double grating while Charles Bell (Alexander Graham Bell's cousin) reflected a beam of sunlight from a mirror onto the grating. While Tainter stayed with the transmitter, Bell went down to the basement of the laboratory with a pair of telephone earpieces connected in series with the selenium cell. When Bell listened to the telephones, he could clearly hear Tainter say "Hoy, hoy" and

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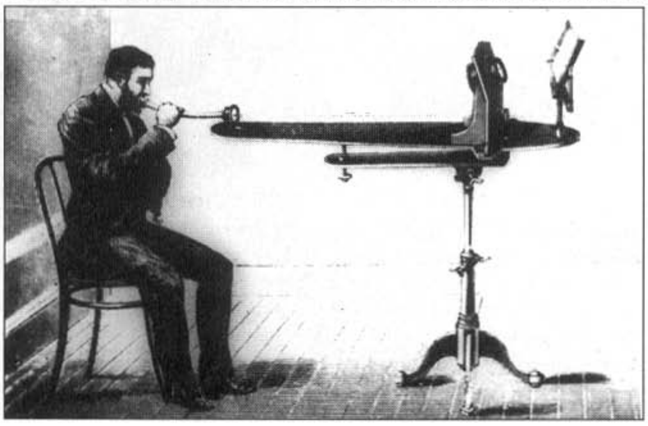


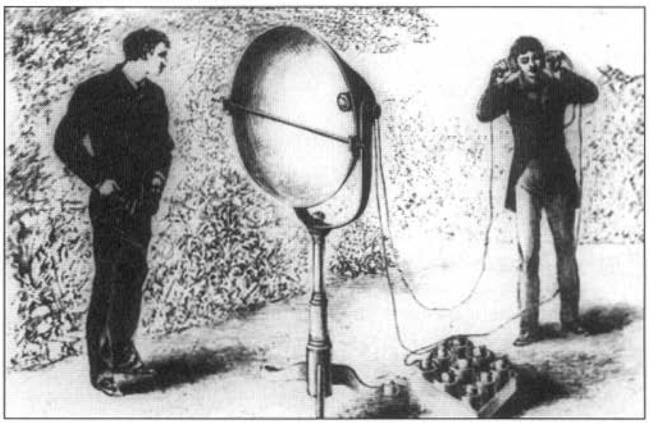
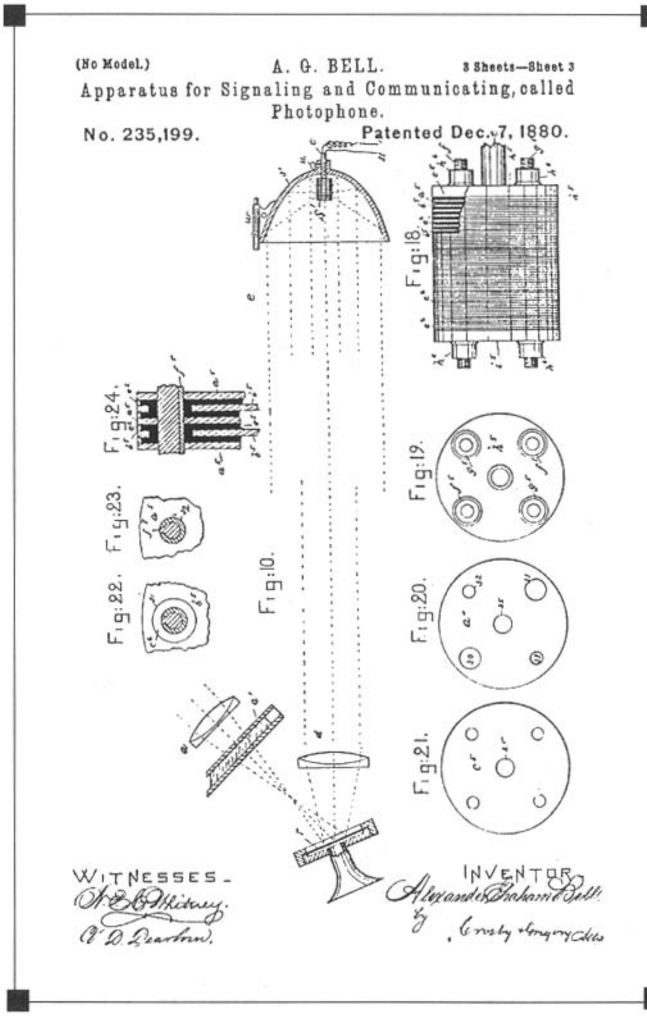


Figure 3 (right). A page from the photophone patent showing the vibrating diaphragm transmitter and selenium detector. The detector was composed of a stack of individual selenium cells connected in parallel. This reduced the resistance to a few hundred ohms, a good impedance match with the telephone earpieces.



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sing "Auld Lang Syne." Bell ended his laboratory notes on that historic day with: "The problem of the reproduction of speech by the agency of light was solved by Mr. Sumner Tainter and myself in my laboratory... on Thursday, Feb. 19, 1880."[16] Eager to establish the priority of their invention, the experiment was demonstrated to witnesses that same afternoon. A few days later, the statements of the witnesses, the photophone apparatus, and a detailed description of the experiment were sealed in a box and deposited in the Smithsonian Institution.

Bell was so excited by the success of the photophone experiment that he proposed naming his newly born second daughter "Photophone," but fortunately for the girl, the name Marian prevailed.[15] With dramatic flair, Bell wrote his father on Feb. 26: "I have heard articulate speech produced by sunlight!...Can imagination picture what the future of this invention is to be!...We may talk by light to any visible distance without conducting wire... In warfare the electric communications of an army could be neither cut nor tapped."[15]

The range of photophonic communication increased quickly. Using a system of lenses to concentrate sunlight on the transmitter grating and to focus the transmitted beam on the selenium detector, successful communication was made over a range of 80 m on April 1. For this experiment, Tainter set up the transmitter in an alley on Massachusetts Ave., while Bell listened at the receiver in a back window of the laboratory. Again, poetic recitations by Tainter were clearly heard.[17] Again, witness statements, apparatus, and notes were bestowed upon the Smithsonian Institution.

Before trying to extend the range of the photophone even further, Bell and Tainter decided to try and improve upon the grating transmitter, which was insensitive to the voice and wasted a lot of the incident light. The gratings were also difficult to make, which was a problem since they kept sending them to the Smithsonian. Although some 50 arrangements were eventually tried,[11] one of Tainter's ideas was finally adopted as the simplest and most reliable. It consisted of a thin glass plate silvered on one side. The vibrations of the speaker's voice caused the plate to become alternately concave and convex. Although the displacement is small, it is enough to affect the divergence and, hence, the intensity distribution of the reflected light beam. Using this modulator and an improved selenium cell in a large parabolic reflector (see Figs. 1 and 2), they were ready to set the distance record for photophonic communication.

That record was set on June 21, 1880. Early in the day, the transmitter of the photophone was installed at a window of the L Street laboratory with the receiver at the top of the Franklin School, about 213 m away. Having anticipated problems in aligning the beam, they had previously installed a telephone line between the two sites. By the time the adjustments were complete, the sun had shifted such that the laboratory window was in the shade. Since this was their last chance to do the experiment before leaving for a conference in Atlantic City the next day,[16] they hastily switched the positions of the receiver and transmitter. Bell later recorded what he heard at the photophone receiver around 4:00 pm: "I then heard a number of sentences perfectly distinctly although the sound was rather faint. ...The one I remember was as follows: 'Mr. Bell if you hear what I say, come to the window and wave your hat'. I immediately did so and Mr. Tainter responded by waving his hat to me." Toward the end of the experiment, Bell heard Tainter say, "Mr. Bell, please talk to me through the telephone."[18]

Elated, and confident that he had revolutionized the world of communication (for the second time), Bell described the photophone publicly in a speech presented to the American Association for the Advancement of Science (AAAS) on Aug. 27. The next day, Bell and Tainter applied for a patent for the photophone that was granted as number 235,199 on Dec. 7, 1880 (see Fig. 3).

Figure 2 (left). These two drawings show Bell operating the photophone transmitter (far left) with Tainter listening at the receiver (left). These drawings first appeared in the same *Scientific American* article as Figure 1.

Significance of the Photophone

At a time when telephones were still few and far between, Bell and Tainter had come up with a system for wireless communication that Bell believed was a step beyond the telephone. Yet sheer technical brilliance was not sufficient for the photophone to find practical application. One problem was that the incoherent light sources available at the time could not produce a sufficiently intense or narrow beam for long range communication. The electric light bulb had just been invented in 1878 (Thomas Edison again) and in its early incarnations produced a light that was too feeble to be of much use. While in France to receive the Volta Prize for his invention of the telephone, Bell brought along a photophone for demonstrations and took the opportunity to do experiments using a "Dubosque" carbon arc lamp, with Monsieur Dubosque assisting. Bell compared the beam of light produced by the lamp to sunlight and for a communication distance of 15 m he described the performance of the photophone with these words: "Articulation loud and perfectly distinct. A grand success."[19] However, no further experiments were done using artificial light sources, and the public seemed perplexed by the experiments using sunlight for communication, which obviously would not work at night or on cloudy days. An unsigned *New York Times* editorial of Aug. 30, 1880, jibbed "Does Prof. Bell intend to connect Cambridge and Boston... with a line of sunbeams hung on telegraph posts, and if so what diameter are the sunbeams to be...what will become of the sunbeams after the sun goes down?...The public has a great deal of confidence in Scientific Persons, but until it actually sees a man going through the streets with a coil of No. 12 sunbeams on his shoulder and suspending it from pole to pole, there will be a general feeling that there is something about Bell's photophone which places a tremendous strain on human credulity."[6] The National Bell Telephone Co. agreed to buy the photophone patent for $2,000, a sum that was intended to cover the two years of research and development. The president, William H. Forbes, remarked less than enthusiastically, "Whether this discovery ever approaches the telephone itself in practical importance or not, it is no less remarkable and a thing which we should be glad to possess."[10]

The fact that a line of sight was required between the transmitter and receiver posed a great difficulty for casual communication, but was no obstacle for military applications. Just as Bell had predicted, the covert nature of light beam communication, unlike radio, made the photophone of great interest to the military. Mims[6] tells the story of the development of line of sight optical communication devices by British, American, German, Italian, and Japanese forces during both world wars. The German "lichtsprecher" used during World War II employed a variation of Bell's double grating transmitter, except that instead of one fixed and one moveable grating, the image of one grating was moved across the fixed grating by means of an electrically controlled mirror. The lichtsprecher could transmit a voice over a distance of 14 km.

Ultimately, the original photophone came to be regarded as a technical curiosity and was never manufactured. By the late 1890s, the significance of the photophone was eclipsed by the success of radio communication.Yet despite its neglect, the legacy of the photophone lives on in modern optical communications. Using lasers and solid state detectors, line-of-sight communication has many military and civilian applications today. Computer data can be transferred over distances of kilometers using optical links that bypass noisy, error prone telephone circuits and at much higher data rates than would be possible by telephone. The next generation of communication satellites may relay data at gigahertz frequencies using laser beams.

In 1921, shortly before his death, Bell said, "In the importance of the principles involved ... I regard the photophone as the greatest invention I have ever made; greater than the telephone."[10] In terms of impact on society, there is not much doubt that the telephone was the more important of the two inventions. But when one considers the importance of optical communication today, the photophone surely deserves an honored place in the history of communication.

A Model Photophone

For our photophone demonstration at the 1992 Optical Science Exhibit contest, we tried to come up with a model that functions according to the principles of the vibrating diaphragm photophone—Bell and Tainter's most successful design. For a light source, we used an ordinary halogen flashlight, which is not only cheap but is also a very bright, well collimated source, not unlike a beam of sunlight. Use of a recognizable flashlight also emphasizes the low-tech nature of the photophone. In the original photophone, Bell and Tainter used a special large microscope coverslide coated with silver for the mirror diaphragm. We were surprised to discover that the same large coverslides are still commercially available. We used one of these slides coated with aluminum in the transmitter. The "articulation" was excellent, just as Bell recorded 113 years ago. It was satisfying to put together the transmitter knowing that it is virtually the same as that of the original photophone.

For the receiver, we used a 10 cm diameter lens and a silicon photodiode detector. An op-amp was used to AC couple and boost the detector signal before going to a small speaker with built-in audio amplifier. Although it would have been interesting to use a variable resistance type selenium photocell in the receiver, they seem to be no longer commercially available. In using a modern detector, we feel that it was worth sacrificing historical accuracy for the sake of good sound quality and a more memorable demonstration. The system functions well for distances up to 15 m (see Fig. 4).

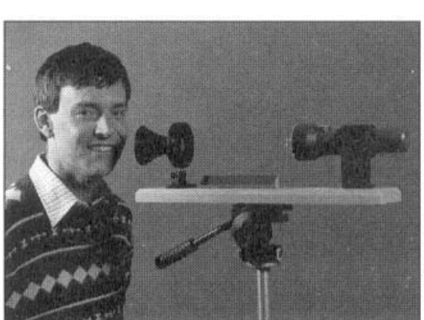

Figure 4. Daniel Hutt with the model photophone used in the Optical Science Exhibit contest at OSA's 1992 Annual Meeting.

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A Model Polarized Light Photophone

In the lab notes of Dec. 6, 1879, only a few months after beginning the photophone project, a sketch appears (in Tainter's hand—see Fig. 5) entitled "Photophone operated by Polarized Light."[14] It shows a collimated beam of light from a candle passing through a Nicol's prism, through a helix of wire, through a second Nicol's prism, and finally to a selenium detector. The helix, or solenoid, is connected in series with a telephone transmitter and battery and thus generates a variable magnetic field inside the solenoid in response to the telephone signal.

Well versed in the scientific literature of the day, Bell was aware of the Faraday effect, in which the plane of polarization of light is rotated for light propagating through many materials in the presence of a magnetic field. In the sketch, the helix is wound about a cylinder containing carbon disulfide, which is a reasonably good Faraday medium (in Bell's day, carbon disulfide was a common laboratory solvent known for its ability to dissolve wax). The idea was to vary the plane of polarization of the light passing through the carbon disulfide, which would then be intensity modulated upon passing through the second Nicol's prism. Today, such a device would be called a Faraday effect modulator. Tainter's sketch represents one of the earliest ideas for an application of the Faraday effect, which was discovered by Michael Faraday in 1845. It is unlikely that Bell and Tainter ever built their Faraday effect modulator. There are no further references to it in their lab notes, and only a few weeks later they were working on the double grating modulator.

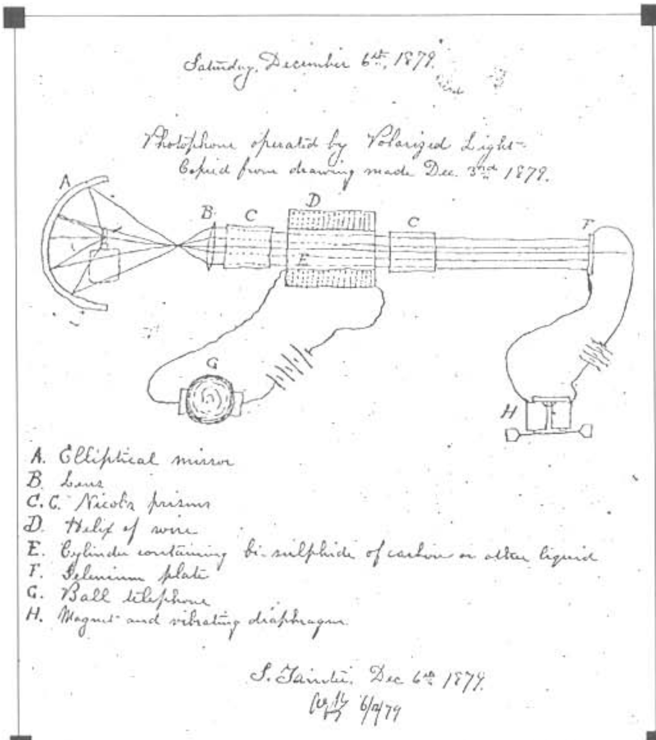

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Figure 5 (top). Drawing by Tainter of the proposed Faraday effect modulator, Dec. 6, 1879.

Figure 6 (bottom). Faraday effect modulator based on Tainter's sketch with which voice and music can be transmitted on a beam of candle light.

We could not resist the temptation to bring Bell and Tainter's idea to life. As a Faraday medium we used a rod of Schott SF-6 glass instead of the noxious and dangerous carbon disulfide. A few calculations showed that reasonable modulation could be achieved using currents of a couple of amps with a rod 6 mm in diameter and 10 cm long with 2000 turns of wire. Instead of Nicol's prisms, we used two pieces of ordinary polaroid sheet (our modulator is shown in Fig. 6). To ensure success, Bell's telephone transmitter and battery were replaced with a 10 W audio amplifier and microphone. The result is rather astonishing. For good dramatic effect, we dim the lights before lighting the candle, then using the receiver from the model photophone described above, we can transmit our voices or music several meters on a beam of candlelight! Bell and Tainter would have been delighted.

Both the model vibrating diaphragm photophone and model polarized light photophone described here were recently donated to the Alexander Graham Bell National Historic Site, Baddeck, Nova Scotia.

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