BLACK HOLE RADIATION: CAN NONLINEAR OPTICS PRODUCE A SIMILAR EFFECT IN SEMICONDUCTORS?

E. YABLONOVITCH
Bell Communications Research, Navesink Research Center
Red Bank, N.J. 07701-7040

ABSTRACT

Shortly after Hawking's prediction of thermal radiation from Black Holes, it became apparent that there were other contexts in which such radiation could appear. For example, it was predicted that accelerating observers are bathed in thermal radiation (Unruh radiation). Even a stationary observer who is looking at an accelerating mirror should see such radiant energy. The effect is very weak, however. An acceleration $g = 980$ cm/sec^2 produces a radiation temperature of only $\sim 4 \times 10^{-20}$ °K, making its detection a major experimental challenge. A nonlinear optical window, whose refractive index is changing rapidly with time appears, to an observer, to be a window into an accelerating world. The sudden injection of a virtual electron-hole plasma into a semiconductor window can change its refractive index on a sub-picosecond time scale, and can produce an apparent acceleration $\sim 10^{20}$g.

It is sometimes mistakenly believed that the black hole concept is a product of 20th century physics. Actually the black hole was first introduced 200 years ago[1,2], and it relied purely on the precepts presented by Isaac Newton, fully 300 years ago. A good starting point is the Newton's Law of the gravitational force between two objects of mass m and M:

$$\text{Force} = \frac{GmM}{r^2} \tag{1}$$

where G is the gravitational constant and r is the distance between the centers of the two objects. As is well-known to college students, the Force Law (1) leads directly to the concept of the "escape velocity" from massive bodies. The gravitational potential energy is simply made equal to the kinetic energy:

$$\frac{GmM}{r} = \frac{mv^2}{2} \tag{2}$$

where v is now the escape velocity.

Two hundred years ago, the Newtonian corpuscular model of light was firmly entrenched, and in addition there was some approximate knowledge of the speed of light, c. It made sense then to think of light as a particle and to ask whether it could escape from a gravitational potential. Taking $v = c$ in eq'n. (2), the mass m cancels from both sides, and we are led to a simple expression for the radius r of a compact body whose gravitational field is strong enough to prevent

light from escaping:

$$r = \frac{2GM}{c^2} \tag{3}$$

The Schwarzschild radius, r, was already known 130 years before General Relativity. In 1784, Michell[1], a leading English astrophysicist came up with the idea during his study of double stars. Independently in France, Laplace[2] writing in 1796 introduced the same concept. The elementary mathematics and physics leading to the Schwarzschild radius, r, is accessible even to a college freshman. By sheer coincidence, the factor 2 originating from the non-relativistic kinetic energy in eq'n. (2), yields the correct relativistic expression in eq'n. (3).

The Schwarzschild radius defines the event horizon of the black hole, the edge beyond which it is impossible to see. By the same elementary approach we can determine the acceleration, a, at the event horizon, which we will find useful later on:

$$a \equiv \frac{GM}{r^2} = \frac{c^4}{4GM} \tag{4}$$

All that we have done so far is based on the physics of 200 years ago. An excellent review of the intellectual history of black holes is given by Werner Israel[3].

We will now skip ahead in time, past Einstein's General Relativity, past the discussions of collapsed stars, right into the 1960's. During that decade, the famous theoretician John Wheeler at Princeton was conducting a serious campaign to improve the understanding of black holes. Uniqueness theorems had recently been proven for the solutions of the gravitational field equations. It had become apparent that the most general black hole could be described by its mass, charge and angular momentum, and nothing more. This led Wheeler and others to the "Black Holes Have No Hair" conjecture. This is whimsical way of saying that there is no fine structure on the surface of black hole which could be used to distinguish one black hole from another. Indeed an uncharged, non-rotating black hole should be fully and uniquely specified by one scalar number, its mass M.

The idea that "Black Holes Have No Hair" led to a paradox, which is illustrated in Fig. 1. A garbage pail can be tossed into the black hole. The garbage pail could contain, for example, old issues of Physical Review which would carry a substantial amount of entropy, i.e. it would require an enormous amount of information to specify the physical state of those pages. However the black hole state can be fully specified by a single scalar number, (its mass M). Upon falling into the black hole, the garbage pail entropy would disappear. This "Wheeler's demon" would violate the Second Law of Thermodynamics. As a solution to waste disposal problems, it is too good to be true.

In 1971, Wheeler addressed this problem to his graduate student, Bekenstein[4]. To resolve the paradox Bekenstein had to attribute some entropy to the black hole, but the only variable at his disposal was the mass M, (for the uncharged, non-rotating case). Since the irreversible combination of two black

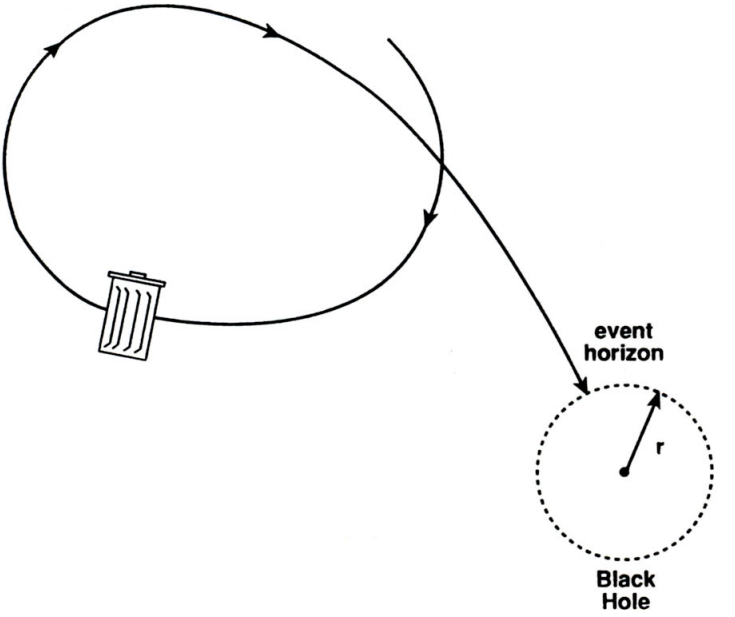

Figure 1: An illustration of the paradox associated with the "Black Holes Have No Hair" conjecture. The garbage pail and its entropy are tossed into the black hole, violating the 2nd Law of Thermodynamics.

holes should have more entropy than the sum of the two, Bekenstein postulated that the entropy should be proportional to mass, M, squared. For the entropy to have units of Boltzmann's constant, K, dimensional analysis required the prefactor to consist of certain combinations of fundamental constants, leading him to the following[5] "ansatz" for the entropy:

$$\frac{S}{K} = \frac{4\pi G}{\hbar c} M^2 \tag{5}$$

where $\hbar \equiv$ Planck's constant$/2\pi$. Thus Bekenstein was able to guess all but the numerical prefactor 4π, which had to await Hawking's work. Since we also happen to know the rest energy of the black hole, $U = Mc^2$, Bekenstein's entropy "ansatz", eq'n. (5), allows us to construct the temperature of a black hole, $T \equiv \partial U/\partial S$:

$$KT \equiv K\frac{\partial U}{\partial S} = \frac{\hbar}{8\pi}\frac{c^3}{GM} \tag{6}$$

With this in hand, Bekenstein showed that the paradox illustrated in Fig. 1 is resolved, and the 2nd Law of Thermodynamics is saved. Amazingly, a small

amount of guesswork led all the way to a black hole temperature.

Bekenstein's gravitational physics colleagues[6] were not amused. They regarded the identification of eq'n. (5) with entropy as incorrect, merely a mathematical coincidence. They were content to abandon thermodynamics and retain the black holes. I find their attitude somewhat surprising since the 2nd Law of Thermodynamics is one of the pillars of physics, while the black hole is a hypothetical object which has never been detected.

Nevertheless, Bekenstein still had one problem which he could not resolve. The black hole could never achieve radiation equilibrium since thermal radiation could fall in, but by definition no electromagnetic radiation could escape from the black hole. Hawking was particularly skeptical of Bekenstein's entropy idea, but within three years, in 1974, he would be the one to rescue it.

Hawking showed[7] that a black hole was also a black body, emitting thermal radiation. This astounding result was contrary to the very definition of a black hole. Hawking's picture, illustrated in Fig. 2, included particles and anti-particles being pulled out of the vacuum in the vicinity of the event horizon. The anti-particle could fall in, while the particle would be emitted. For us the picture can be simpler. Since the temperature will be low in our discussion, the photon is the only particle which is energetically accessible, and since the photon is its own anti-particle, this can all be summarized by a simple, thermal spectrum of low energy photons.

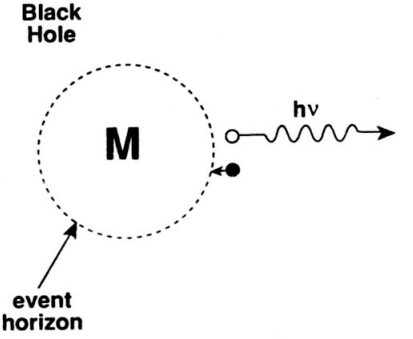

Figure 2: Particle and anti-particle emission from black holes. We need only consider the photon, which is its own anti-particle.

Hawking derived eq'n. (6) from quantum electrodynamics[7], supplying the numerical factor that had been missing from Bekenstein's equations. For a black hole of mass equal to our sun, the temperature is only $\approx 6\times 10^{-8}$ °K. A flurry of checking and re-checking was triggered by this prediction. Other theorists wanted to find alternate ways of deriving the same result, and to find more examples of the same type of effect. Within months, it became apparent that there was a more general phenomenology. To see this let us combine the acceleration at the event horizon, eq'n. (4), based on eighteenth century physics, and the temperature,

eq'n. (6), based on Bekenstein's "ansatz":

$$KT = \frac{\hbar}{2\pi}\frac{a}{c} \tag{7}$$

Re-interpreted, eq'n. (7) means that the thermal radiation is associated with the acceleration, a, and does not require black holes. Indeed, exactly this was proven by Unruh[8] and Davies[9] shortly after Hawking's work. Observers of the electromagnetic field in an *accelerating reference frame* should see thermal radiation at a temperature T. Black holes are not required! Today, the black hole temperature eq'n. (6), is regarded as a special case of the more general and elegant-looking Unruh radiation temperature, eq'n. (7). The effect as seen by an accelerating observer on a rocket ship is illustrated in Fig. 3:

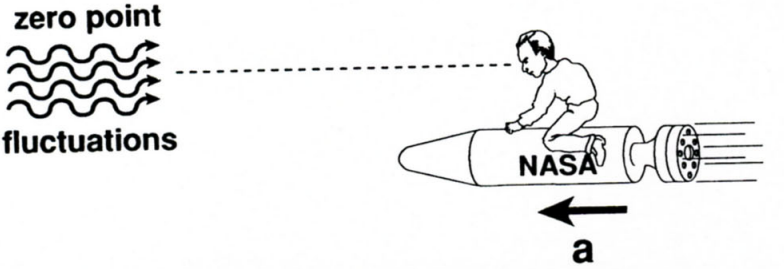

Figure 3: An observer on an accelerating rocket looks out at the zero point electromagnetic field, but sees a finite thermal excitation above the zero point as given by eq'n. (7).

The basic physical mechanism for this radiation is that zero point quantum fluctuations in an inertial frame become transformed into real thermal photons when Fourier analyzed in terms of the photon modes of the accelerating frame. In a frame experiencing linear acceleration at $g = 980$ cm/sec^2, equivalent to the acceleration experienced at the earth's surface, this thermal radiation is at a temperature of only 4×10^{-20} °K.

Thus emerges the pattern of our discussion. What started out as an esoteric effect in black holes, now merely requires an impossibly large acceleration of the observer. Presently, we will find that the observer can be stationary and that large accelerations are required only for a mirror. Following that, we will see that an accelerating mirror is actually not needed, a rapidly changing refractive index will do. At each step we get closer to an experiment that can actually be performed with present-day technology!

Now we will see that the observer need not experience the acceleration himself. DeWitt[10], Fulling[11] and Davies[12] argued that the zero point field fluctuations near an accelerating mirror are already being subjected to an accelerating motion. In effect, the moving mirror forces a relative accelerating motion between the electromagnetic quantum fluctuations and a stationary observer. Remarkably, the conversion of zero point quantum fluctuations into real thermal photons is equally effective whether the mirror is advancing toward the observer or receding away from him. This is illustrated in Fig. 4:

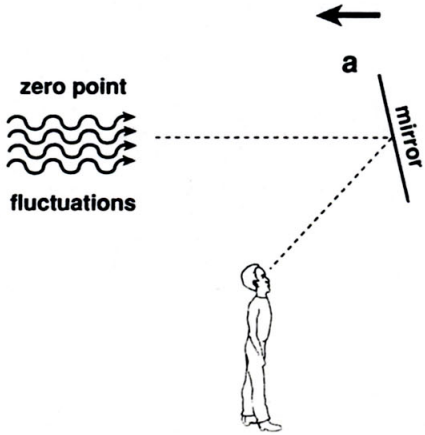

Figure 4: An observer looking at the reflection of the zero point electromagnetic field in an accelerating mirror. The relative motion of the field and the observer is the same as if the observer were on the rocket ship of Fig. 3. The stationary observer sees a finite thermal excitation above the zero point.

One of Davies' papers[12] had an interesting title, "Radiation From Moving Mirrors and Black Holes". The origin of the acceleration effects is similar in both cases as illustrated in Fig. 5. In front of the mirror is a zero point photon standing wave. As the mirror accelerates, the node of the standing wave remains tied to the its surface, and the standing wave pattern is accelerated along. Likewise, zero point fluctuations are constantly being pulled into the black hole. In both instances zero point fluctuations are being accelerated relative to an observer, giving rise to a finite excitation above the zero point.

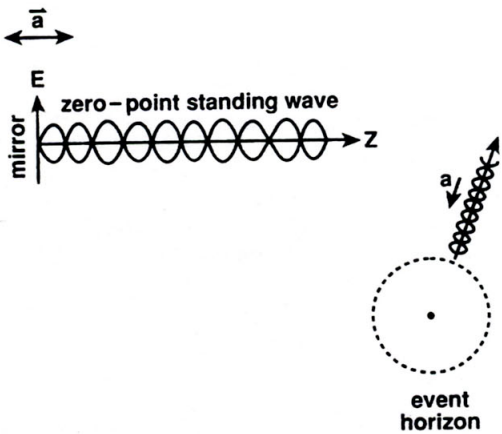

Figure 5: Two ways of accelerating zero point fluctuations, by gravitational attraction, and by means of an accelerating mirror.

How to create a moving mirror? Couldn't nonlinear optics be defined as doing "tricks" with moving mirrors? During the mid-1970's, when all these

wonderful theoretical ideas were being derived, I was specializing in nonlinear optics and doing[13] laser induced plasma experiments. For example, a CO_2 laser would be focused in air, transforming it into a plasma. Before the ionization event the refractive index of the air was unity. Afterward, the overdense plasma would have a refractive index of zero. The phase modulation associated with such an index change was shown[13] to produce nearly a 10% blue shift in the transmitted laser photon energy, a very substantial effect. Likewise, in a semiconductor, the sudden creation of electron-hole pairs can reduce the refractive index from ~3.5 to 0 in a very brief time period.

Now let us imagine looking through one of these windows, of thickness z, whose refractive index is changing. The optical path is $n \times z$, the phase shift is $nz\omega/c$ and the frequency shift is $\dot{n}z\omega/c$ where n(t) is the time-dependent window refractive index and ω, is the incident angular frequency. To the observer looking at a laser in transmission through the window, its frequency appears to be Doppler shifted by the velocity $\dot{n}z$. This window sees a fast moving world, a Doppler-shifted world. The equivalent velocity is given by:

$$\omega + \Delta\omega = \omega(1 + \frac{v}{c}) \tag{8}$$

Suppose further, at the next order of approximation, that the frequency shift $\Delta\omega$ becomes a frequency chirp $\dot{\omega}$. Then,

$$\omega + \dot{\omega}t = \omega(1 + \frac{at}{c}) \tag{9}$$

The apparent Doppler shift is now changing with time. It appears to the observer that the image in the window is accelerating.

Therefore we can regard such a gas plasma or a semiconductor slab as an observational window on an accelerating world. The main point of our discussion[14] is that *frequency chirp is equivalent to acceleration*. Chirp is ubiquitous in nonlinear optics. The relative motion of the observer and the electromagnetic field is controlled by the rate of refractive index change or alternatively by the time varying plasma density as illustrated in Fig. 6:

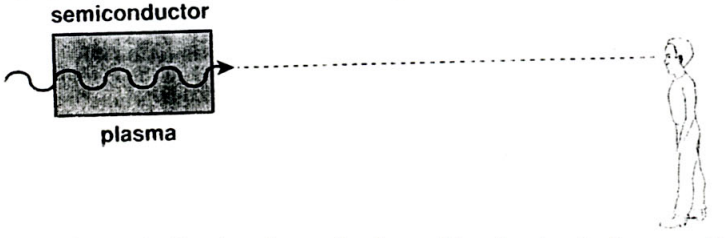

Figure 6: An observer looking through a semiconductor slab and seeing the frequency chirped image. For the observer this seems like a window into an accelerating world.

We may speak alternately, in acceleration units, or in chirp rate units. Equation (9) shows that:

$$a = c\frac{\dot{\omega}}{\omega} = \frac{c}{\tau} \tag{10}$$

where τ is a characteristic chirp time. For $\tau = 10^{-13}$ sec, well within current sub-picosecond technology, the acceleration c/τ is 3×10^{23}cm/sec^2 or $\approx 3\times 10^{20}$g. According to eq'n. (7) this is enough to produce an Unruh radiation temperature of a few degrees Kelvin, with frequencies extending into the millimeter wave band.

Let us now make a brief digression towards quantum field theory. The operative mechanism is that frequency chirp is produced by a changing refractive index. The normal modes of the electromagnetic field which exist at the outset of the experiment, are different from the new normal modes which have adapted to the changed refractive index. A zero point excitation in the original normal modes might have to expanded in terms of zero *and* finite photon-number wave-functions of the new modes. The mathematical recipe for this transformation is called the Bogolyubov Transformation. Let $A(z,t)$ be a quantum field operator which can be written as a linear combination of the original normal modes $\mathbf{A}_k(z,t)$:

$$A(z,t) = \sum_{\text{all } k} [a_k \mathbf{A}_k(z,t) + a_k^+ \mathbf{A}_k^*(z,t)] \tag{11}$$

where a_k and a_k^+ are the annihilation and creation operators appropriate to these normal modes which might be, for example, the standard plane waves:

$$\mathbf{A}_k(z,t) = c[2\pi\hbar/\omega]^{1/2}\exp\{i(kz - \omega t)\} \tag{12}$$

As the refractive index changes, the quantum field operator $A(z,t)$ can be re-written in terms of the new normal modes $\bar{\mathbf{A}}_k(z,t)$ which solve Maxwell's eq'ns.

$$A(z,t) = \sum_{\text{all } k} [b_k \bar{\mathbf{A}}_k(z,t) + b_k^+ \bar{\mathbf{A}}_k^*(z,t)] \tag{13}$$

where b_k and b_k^+ are the new annihilation and creation operators. The Bogolyubov transformation consists of writing the new operators as a linear combination of the original operators:

$$b_k = \sum_{k'} (\alpha_{kk'}^* a_{k'} - \beta_{kk'}^* a_{k'}^+) \tag{14}$$

A key role is played by the coefficients $\beta_{kk'}$ which measure the admixture of annihilation and creation operators, or equivalently the admixture of positive and negative frequency modes. The expectation value of the accelerated mode k photon-number operator, in the original zero point state, $|0>$, is:

$$<0|\, b_k^+ b_k \,|0> = \sum_{k'} \left|\beta_{kk'}\right|^2 \tag{15}$$

For case of a step-function change of refractive index from n_o to n at time $t=0$, the transformation is straightforward:

$$\alpha_{kk'} = \delta_{kk'}(n + n_o)/2\sqrt{n_o n} \quad \text{and} \quad \beta_{kk'} = \delta_{kk'}(n - n_o)/2\sqrt{n_o n} \tag{16}$$

where $\delta_{kk'}$ is the Kronecker delta. We see that in this example, the induced

photon occupation number can be of order unity, and will have a frequency independent spectrum. In a finite duration pulsed laser experiment, as in this case, the spectrum will generally be non-thermal. An *exact* thermal spectrum evolves only asymptotically[14] at infinitely long times. In that respect we fail to exactly mimic a black hole. This concludes our digression into quantum electrodynamics.

In the remainder of this article let us discuss how to implement these ideas in a real experiment. Basically, we require an optical nonlinearity in a real material, capable of a substantial refractive index change. The index change associated with an electron-hole plasma in a semiconductor satisfies this requirement. A very small density of carriers results in a very large index change in the microwave spectral region. This is due to the zero-frequency resonant character of the plasma dielectric response. Such a low frequency dielectric response is well-matched to eq'n. (7), which restricts us to low "effective Unruh temperatures" at the moderate accelerations which are experimentally achievable.

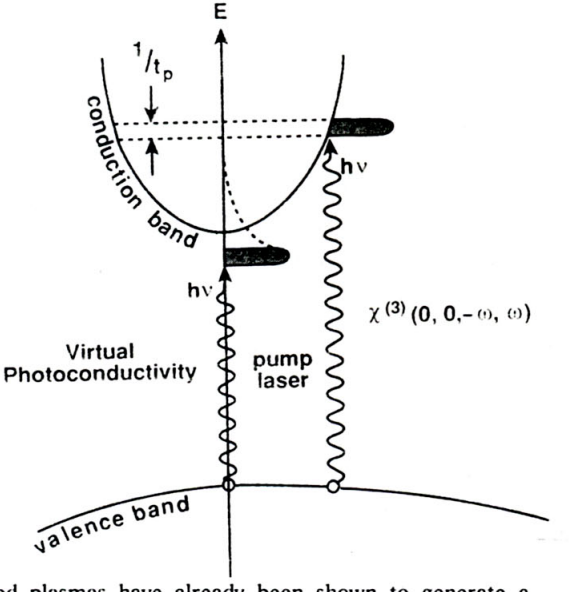

Figure 7: A comparison of transitions from the valence band to the conduction band in ordinary photoconductivity and in virtual photoconductivity. The electron population distribution for the two cases is illustrated by the dashed lines. The frequency width $1/t_p$ corresponds to the real electron distribution induced by ordinary photoconductivity. Virtual photoconductivity, due to non-absorbed photons, has the advantage of being purely reactive and non-dissipative.

Since laser produced plasmas have already been shown to generate a substantial frequency chirp, this nonlinearity would seem promising. Furthermore, a semiconductor crystal is readily cooled to 1°K, reducing background thermal radiation in the microwave region. There remains one problem however. The free electrons and holes in the optically injected semiconductor plasma will experience mutual collisions. These collisions will generate bremstrahlung radiation in the microwave region, a background effect that could mask the Unruh radiation. We would prefer to find a purely reactive nonlinearity in which dissipative absorption of the incident laser beam is absent. Instead of creating real

electrons and holes, one could tune the incident laser beam in the transparent region just below the semiconductor band edge, creating[15] virtual electron-hole pairs. The distinction is illustrated in Fig. 7.

The change of zero-frequency electric susceptibility induced by optical photons of energy $h\nu = \hbar\omega$, conventionally a third-order nonlinear susceptibility $\chi^{(3)}(0, 0, -\omega, \omega)$, has been given various names in the past, including virtual photoconductivity, the inverse quadratic electro-optic effect, and in the case of quantum wells, the AC-DC Stark effect[16]. Since this particular susceptibility is resonant at the band edge, for small detunings it will dominate other nonlinearities such as two-photon absorption which is parity-forbidden at zone center.

The effect of virtual electron-hole pairs is large because they behave as though bound by the small detuning energy and are therefore highly polarizable. Calculations of virtual photoconductivity have recently been extended[17] to the limit of very strong optical fields. The change of low frequency dielectric constant saturates at ~ 1 unit for an optical intensity of $\sim 10\ \mathrm{MW/cm^2}$, for reasonable detunings. Different experimental geometries suggest themselves for the excitation of the semiconductor slab, as illustrated in Fig. 8:

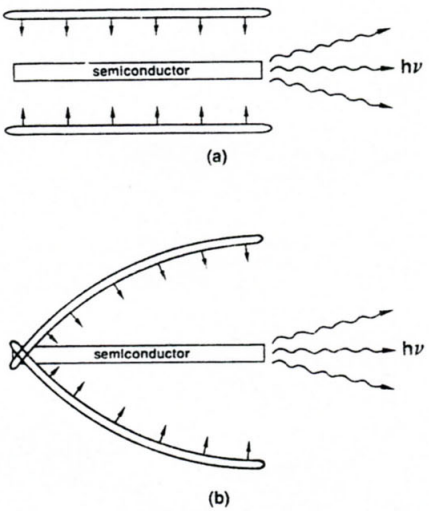

Figure 8: Two possible experimental geometries for exciting a semiconductor slab dielectric waveguide for millimeter waves. The pancake-shaped objects are the incident sub-picosecond optical pulses. In (a), the pancake-shaped sub-picosecond pulses bombard the semiconductor slab simultaneously throughout, mimicking the step function model we solved earlier. In (b) there is a traveling wave excitation, which, due to the incident angle of optical pulses, sweeps down the slab faster than the speed of light. The emitted microwave photons are written as $h\nu$. This not a Cerenkov effect since polarizability, not polarization is moving faster than the speed of light.

There is yet another way of thinking about this effect, by making contact with the famous Casimir[18] Force between metal plates, as illustrated in Fig. 9. This Force can be thought of as arising from zero-point energy of the electromagnetic field. It is therefore regarded as one of the most direct experimental manifestations of the reality of the quantum field. Between two closely spaced metallic plates, long wavelength electromagnetic field modes are unable to fit. Outside the plates these modes exist, and their zero-point mean-square field exerts an unbalanced pressure on the plates.

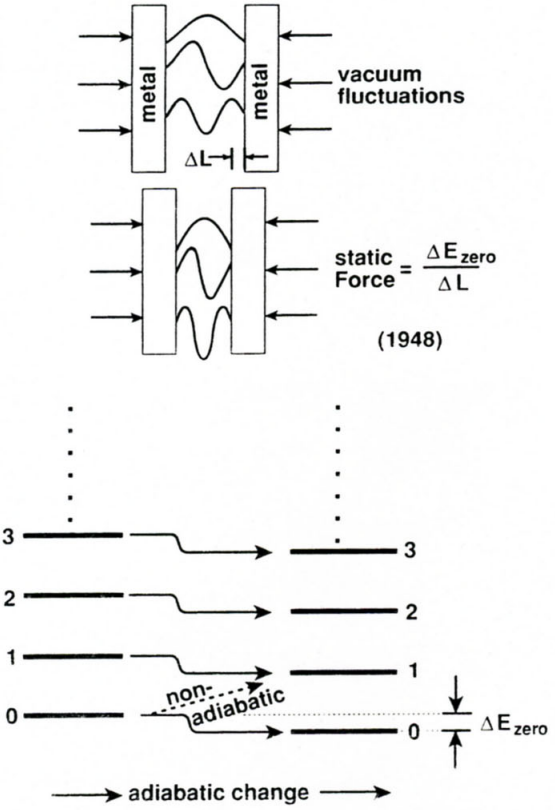

Figure 9: The Unruh radiation, re-interpreted as a non-adiabatic Casimir effect. The Casimir force is calculated by making a slow, adiabatic, differential displacement ΔL of the spacing between the plates. This changes the entire ladder of harmonic oscillator levels representing the electromagnetic field. Adiabatically, the zero-photon energy level goes into a new zero-photon level, the one-photon level goes into a new one-photon energy level, etc. The adiabatic shift in zero point energy is ΔE_{zero}. The Casimir Force is then the differential energy divided by differential displacement, $\Delta E_{zero}/\Delta L$. This is one possible way of calculating the Force. Now what if the displacement change was large, very sudden, and too fast for the electromagnetic field to respond adiabatically. Then there would a small probability of a non-adiabatic transition, for example from the old zero-photon level to the new one-photon level, as illustrated. Such one-photon and multiphoton states are what we would hope to detect.

In effect, when the metal plates are brought together, the empty space between them becomes filled with the electron plasma of the metal. If this is done very quickly, the zero point electromagnetic field has no time to re-adjust adiabatically and suffers non-adiabatic excitation in the course of trying to escape from the forbidden region between the plates. Likewise, a semiconductor slab may be filled with zero point electromagnetic fields. If suddenly the semiconductor were converted to a plasma, by electron-hole excitation, the zero-point electromagnetic field would be abruptly forced to escape from that forbidden volume. In doing so, there would be some probability of non-adiabatic excitation, leading to real photons.

The design of an experimental configuration for generating and detecting this radiation owes much to Heinrich Hertz, who first made radio waves 100 years ago, and to the more modern photoconductive switches[18] which have been used with mode-locked lasers to generate millimeter waves. H. Hertz used the switching action of a spark gap to generate radio waves. Likewise, a fast

photoconductor, when illuminated by a sub-picosecond light pulse, will conduct a burst of current which radiates in the millimeter wave spectral region. Such a configuration is shown in Fig. 10. Cleverly, a photoconductor can be used both as a generator and coherent detector of the radio waves. The detector switch is turned on by a synchronous optical pulse from the same mode-locked laser. If the detector photoconductor is in the on-state for one-half cycle of the millimeter wave electric field, a small dc current will be pushed through. If this repeats for every pulse in the mode-locked train, the average current can be monitored by a pico-ammeter.

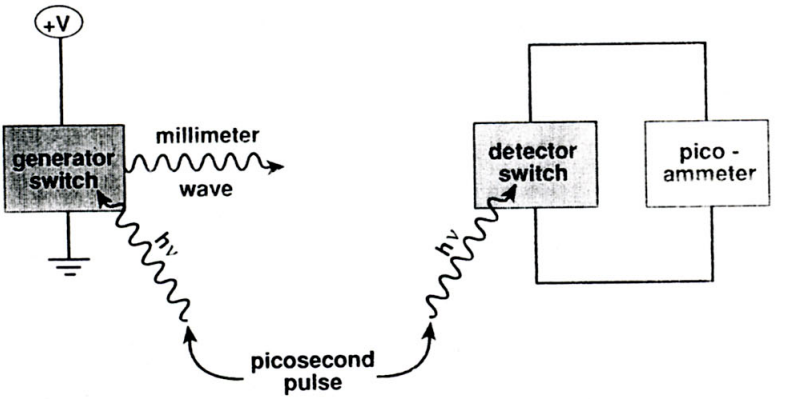

Figure 10: Photoconductive switches are turned "on" by a picosecond optical pulse. The generator switch, biased at voltage + V, produces a millimeter wave which drives a very tiny electric current through the detector switch.

Suppose that the bias voltage + V were disconnected. It might seem that there would be no millimeter wave signal at all. But the generator photoconductor is always experiencing a fluctuating bias field from zero-point electromagnetic waves. In an octave bandwidth around 500 GHz, the zero-point field strength magnitude averages a few tens of milliivolts per cm, small but not negligible. This assures a signal even in the absence of an overt bias voltage.

In our case, of course, we would use a virtual photoconductor which changes its dielectric constant rather than its conductivity. Radiation produced this way would be equivalent to Unruh radiation. It would be detected by conventional photoconductivity in the detector switch, acting as a radio mixer. Employing a similar arrangement as Fig. 10, the photoconductive switch has been shown[19] to have extremely low noise, such that signals as weak as quantum noise can be detected readily. Such radio receivers are finding increasing[18,19] use in opto-electronic technology. The noise temperature is not so low, but fortunately the detector switch has little or no noise in the waiting period between successive picosecond pulses. The noise is present during the picosecond switching pulse only.

An experimental geometry more appropriate to this experiment is shown in Fig. 11. The generator is a slab of GaAs cooled to ~1°K and thick enough to support waveguide modes in the millimeter wave band. Therefore the slab would contain zero point electromagnetic waves.

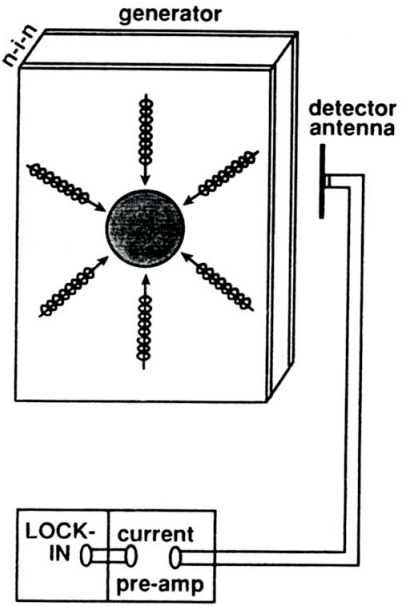

Figure 11: A picosecond laser pulse at normal incidence is transmitted through the center of the slab, generating a local population of virtual carriers, indicated by the shaded region in the center of the slab. Virtual carriers, unlike real carriers, cause an increase rather than a decrease in the local dielectric constant. This would pull the waveguided zero-point electromagnetic field fluctuations (illustrated as standing waves) toward the laser spot, as shown. Since virtual photoconductivity is purely reactive, the dielectric constant would return to normal on the trailing edge of the laser pulse. The excess concentration of field fluctuations at the center of the laser spot would then be expelled. The detector photoconductive switch, designed as an antenna and located at the slab periphery, would initially see a reduction in zero-point noise in synchronism with the leading edge of the laser pulse and then an increase in noise as the field fluctuations were expelled on the trailing edge of the pulse.

The experimental signature of accelerated zero-point fluctuations is very clear in this experiment, since there is no other mechanism which could cause a reduction of noise below normal quantum fluctuations. In that respect it resembles the noise reduction seen in optical squeezing[20] experiments. The increase of noise on the trailing edge of the laser pulse is much less definitive, since inadvertent bremstrahlung or other noise mechanisms could be responsible.

Since a reduction in mean-square noise power is the experimental signature, discrimination against coherent signals is quite easy. Nevertheless, it is best to minimize coherent signals by diminishing any stray electric fields inside the GaAs generator slab. Accordingly the slab is doped n-i-n to minimize doping-induced fields, and the laser beam should avoid the periphery of the slab where there are depletion fields.

CONCLUSION:

In this paper I chose to introduce the excitation of the zero-point electromagnetic field by means of black holes, Hawking radiation and Unruh radiation. It should be obvious by now that this approach is only one of many possible choices. In Fig. 9, we gave an alternate interpretation in terms the non-

adiabatic Casimir effect. On the other hand, those who are experts in optical squeezing[20] may insist that this effect is merely a case of single-cycle millimeter wave squeezing. Other observers will call this the parametric excitation of the vacuum, still others, the inverse quadratic electroptic effect by virtual photoconductivity with zero-point-photon input waves. There are many choices.

But there is one final explanation which I prefer the most; the hand waving explanation. Consider the human hand. Being mainly composed of water, no doubt its dielectric constant differs greatly from unity. As we wave our hand, indeed as we walk through life, unbeknownst to us, we are forcing the zero-point electromagnetic field to constantly change and adapt to us. This all takes place automatically, adiabatically and almost imperceptibly since the Casimir forces are so weak. What if we were to make a sudden, abrupt, motion of our hand that is so quick, that the zero-point electromagnetic field could not respond adiabatically? The quantum field would make itself felt. Our hand-waving would generate a few detectable microwave photons.

Let us thank Prof. Bloembergen for bringing us into this marvelous subject!

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