② Where Does All the Energy Go?

Suppose we have a Michelson interferometer (see the section: Basics of Interferometry and Interferometers) set up with a perfectly collimated (plane wave source) and perfectly plane mirrors adjusted so that they are perfectly perpendicular to the optical axis (for each mirror) and the beamsplitter is also of perfect construction and oriented perfectly. In this case, there won't be multiple fringes but just a broad area whose intensity will be determined by the path-length difference between the two beams. Where this is exactly 1/2 wavelength (180 degrees), the result will be nothing at all and the screen will be absolutely dark! So, where is all the energy going? No, it doesn't simply vanish into thin air or the ether, vacuum, the local dump, or anywhere else. :-)

Your initial response might be: "Well, no system is ideal and the beams won't really be perfectly planar so, perhaps the energy will appear around the edges or this situation simply cannot exist - period". Sorry, this would be incorrect. The behavior will still be true for the ideal case of perfect non-diverging plane wave beams with perfect optics.

Perhaps, it is easier to think of this in terms of an RF or microwave, acoustic, or other source:

- What would happen if a continuous wave signal were split into two parts and then recombined 180 degrees out of phase? Or a sinusoidal signal from a quartz oscillator split into two equal parts on a pair of transmission lines (coax or whatever) and recombined 180 degrees out of phase? Less mysterious?
- Assuming energy doesn't actually disappear (it doesn't), what else must be going on to account for a null at the point where they combine? What does each signal see? How is it affected?
- What about with just an acoustic resonance inside an organ pipe or even a low-tech standing wave on a piece of string? Oops, Did I say resonance and standing waves? :-)

Hint: From the perspective of either of the two signals, how is this different (if at all) than imposing a node (fixed point) on a transmission line? Or at the screen of the interferometer? After all, a nodal point is just an enforced location where the intensity of the signal MUST be 0 but here it is already exactly 0. For the organ pipe, such a nodal point is a closed end; for the string, just an eye-hook or a pair of fingers!

OK, I know the anticipation is unbearable at this point. The answer is that the light is reflected back to the source (the laser) and the entire optical path of the interferometer acts like a high-Q resonator in which the energy can build up as a standing wave. Light energy is being pumped into the resonator and has nowhere to go. In practice, unavoidable imperfections of the entire system aside, the reflected light can result in laser instability and possibly even damage to the laser itself. So, there is at least a chance that such an experiment could lead to smoke!

(From: Art Kotz (alkotz@mmm.com).)

We don't have to to think all that hard to figure out where all the energy is dissipated in a Michelson interferometer. Nor do we have to refer to imperfect components either. The thought experiment of perfect non-absorbing components still renders a physically correct solution.

To summarize a (correct) previous statement, in a Michelson interferometer with flat surfaces, you can get a uniform dark transmissive exit beam. The power is not dissipated as heat. There is an alternate path that light can follow, and in this case, it exits the way it came in (reflected back out to the light source).

In fact, with a good flat Fabry-Perot interferometer, you can actually observe this (transmission and reflection from the interferometer alternate as you scan mirror spacing).

In the electrical case, imagine a transmitter with the antenna improperly sized so that most of the energy is not emitted. It is reflected back to the output stage of the transmitter. If the transmitter can't handle dissipating all that energy, then it will go up in smoke. Any Ham radio operators out there should be familiar with this.

(From: Don Stauffer (stauffer@htc.honeywell.com).)

Many of the devices mentioned have been at least in part optical resonators. It may be instructive to look at what happens in an acoustic resonator like an organ pipe or a Helmholtz resonator.

Let's start with a source of sound inside a perfect, infinite Q resonator. The energy density begins to build up with a value directly proportional to time. So we can store, theoretically, an infinite amount of acoustic energy within the resonator.

Of course, it is impossible to build an infinite Q resonator, but bear with me a little longer. It is hard to get an audio sound source inside the resonator without hurting the Q of the resonator. So lets cut a little hole in the resonator so we can beam acoustic energy in. Guess what, even theoretically, this hole prevents the resonator from being perfect. It WILL resonate.

No optical resonator can be perfect. Just like in nature there IS no perfectly reflecting surface (FTIR is about the closest thing we have). Every time an EM wave impinges on any real surface, energy is lost to heat. With any source of light beamed at any surface, light will be turned into heat. In fact, MOST of the energy is immediately turned to heat. By the laws of thermodynamics, even that that is not converted instantaneously into heat, but goes into some other form of energy, will eventually turn up as heat. You pay now, or you pay later, but you always pay the entropy tax.

(From: Bill Vareka (billv@srsys.com).)

And, something else to ponder:

If you combine light in a beamsplitter there is a unavoidable phase relation between the light leaving one port and the light leaving the other.

So, if you have a perfect Mach-Zehnder interferometer like the following

```
+-------+      BS         M
| Laser |=====>[¥]--------¥
+-------+       |         |        M = Mirror
                |         |       BS = Beamsplitter
                |      BS |
              M ¥--------[¥]---->A
                          |
                          |
                          V
                          B
```

If you set it up so that there is total cancellation out of, say, port A, then Port B will have constructive interference and the intensity coming out port B will equal the combined intensity coming in the two input ports of that final beamsplitter. This is due to the phase relation between the light which is reflected at the beamsplitter. That which is reflected and goes out port A will be 180 degrees out of phase with that which is reflected and goes out port B. The transmitted part of port A and port B are the same. Hence the strict phase relationship between the light from the two output ports. This is an unavoidable result of the time-reversal symmetry of the propagation of light.

(From: A. Nowatzyk (agn@acm.org).)

A beam-splitter (say a half silvered mirror) is fundamentally a 4 port device. Say you direct the laser at a 45 degree angle at an ideal, 50% transparent mirror. Half of the light passes through straight, the rest is reflected at a 90 degree angle. However, the same would happen if you beam the light from the other side, which is the other input port here. If you reverse the direction of light (as long as you stay within the bounds of linear optics, the direction of light can always be reversed), you will see that light entering either output branch will come out 50/50 on the two input ports. An optical beam-splitter is the same as a directional coupler in the RF or microwave realm. Upon close inspection, you will find that the two beams of a beam-splitter are actually 90deg. out of phase, just like in an 1:1 directional RF coupler.

In an experiment where you split a laser beam in two with one splitter and then combine the two beams with another splitter, all light will either come out from one of the two ports of the second splitter, depending on the phase. It is called a Mach-Zehnder interferometer.

Ideal beam-splitters do not absorb any energy, whatever light enters will come out one of the two output ports.