MITOCW | Laser fundamentals II: Laser linewidth | MIT Video Demonstrations in Lasers and Optics

SHAOUL EZEKIEL: This next demonstration is about the laser line width or the spectral width of the laser radiation. Now theory predicts that the line width of a laser should be very, very narrow, much narrower then a fraction of a Hertz, in fact, of the order of 10 to the minus 3, 10 to the minus 4 Hertz or even smaller. In practice, we don't see that.

In practice, if you measure the laser line width, you find sometimes it's hundreds of kilohertz, megahertz, and even tens or hundreds of megahertz. So what is really going on here, then? What's the discrepancy between theory and practice?

In order to explain what's going on, I'm going to review some fundamentals about lasers. Here is a laser, simple laser. It's made up of a helium neon discharge tube. And the discharge tube is terminated by two mirrors. And there's nothing else inside the cavity besides the discharge tube and the two mirrors.

Now the cavity resonance associated with this length cavity, then, is certainly determined by the length of the cavity and the refractive index of the medium between the two mirrors so that if we have a cavity resonance within the bandwidth of the helium neon amplifier, then-- and then we have, of course, gain that's bigger than the losses in the cavity-- then we'll have oscillation at the cavity resonance. So then the frequency of the laser is determined by the cavity resonance that is within the bandwidth of the amplifier.

So the frequency, then, will fluctuate if the optical length of the cavity will fluctuate due to, let's say, due to temperature, vibrations, fluctuations in the power supply, that changes the refractive index and so on. So in practice, then, the laser frequency will just move all over the place depending on the mechanical design of the laser.

So that if you want to measure this line width, this practical line width of a laser, then you would take-- one way of doing it is to take two such lasers oscillating at a single frequency in each one of them. And then you beat them. And you look at the beat on an electronic spectrum analyzer. And you'll find that that beat is, as I mentioned before, can vary anywhere from hundreds of megahertz down to a few kilohertz depending, again, on the design of the laser.

In order to measure or observe the intrinsic line width-- this is the line width that's predicted by Shallon Town many, many years ago, this line width is of the order of, as I said before, 10 to the minus 3, 10 the minus 4 Hertz for a 1 milliwatt laser. This width is due to fundamental noise sources such as spontaneous emission. And it doesn't depend on any length of the cavity and the optical length of the cavity. Here, we assume that everything else is fixed. But only the spontaneous emission is giving us the residual line width.

In order to measure this fundamental line width, it's very difficult to do it by using two lasers. Because it's very difficult to stabilize the length of the cavities in each laser. There are techniques using wide band feedback stabilization loops to reduce the vibrations and the drift of a laser cavity. But still, it still would be difficult to reach the fundamental line width.

So in this demonstration, we're going to give you a feel for how small the laser line width can be using some simple concepts. Before I go on to describe what we're going to do, I'm going to show you what an ideal way of measuring or observing the laser line width is.

Here is a ring cavity made up of three mirrors. Here's one mirror, another mirror, another mirror. It's a triangular cavity. Here's the cathode. And there are two anodes, one over here and one over here. So we have, say, helium neon discharged within the resonator.

Because it's a ring, we're going to get two laser oscillations, one in the clockwise direction and the other one in the counterclockwise direction. If we take the two outputs and we beat them, then the beat frequency will give us essentially the sum of the two individual spectral widths of the two laser frequencies. Now, because the cavity is common to both and the refractive index variations are common to both frequencies, then this would give you probably about the best measurement of the true line width or the intrinsic line width of the laser.

But that's not what we're going to demonstrate here. What we're going to use, we're going to use our simple laser here. And because of the length of this cavity, we get two modes, two cavity modes that are within the bandwidth of the helium neon amplifier. And since the cavity is common to both modes, except for the fact that they are separated by c over 2L where c is the velocity of light and an L is the optical length of the cavity, other than that, the fluctuations and the drift of the cavity should be common to both. So by then beating the two outputs associated with these two modes in this laser on an electronic spectrum analyzer, then the line width that we'll measure with the electronic spectrum analyzer will give us a measure of how narrow the spectral width of the individual laser is.

The set up we're going to use is over here. Now, in this box I have a laser just like this. The reason why we use this box is to keep the environment at a constant temperature, or as close to constant temperature as possible and also to isolate against vibrations so that the laser cavity is not shaking too much.

The output from the laser goes through a polarizer. Now, since this cavity is made up of internal mirrors-- there's nothing else between the two mirrors except for the discharge tube-- the two modes that will oscillate will have orthogonal polarization. So that by using a polarizer like this, I can select either frequency. Or, if I put it 45 degrees, I can select both laser frequencies.

So after the polarizer, then, I reflect the light by this mirror, and then this mirror, onto an optical spectrum analyzer, which is a scanning Fabry-Perot interferometer. Now the length of this scanning Fabry-Perot is about 10 centimeters, which means that the free spectral range is about 1 1/2 gigahertz.

So now we are ready to look at the output of this spectrum analyzer on an oscilloscope over here. We see the output when we have the polarizer adjusted so that only one laser frequency is allowed to be observed by the scanning Fabry-Perot interferometer. What we're seeing is the free spectral range of the scanning Fabry-Perot, which is 1 1/2 gigahertz. So, as you can see, eight big boxes and corresponds to 1 1/2 gigahertz. And the laser is oscillating at a single frequency.

Now let me adjust the polarizer so that I bring up the other mode, as observed by the scanning Fabry-Perot. Now you can see that the other laser frequency is about three big boxes away from here, from this mode, which means that the separation if you do your arithmetic, since eight boxes corresponds to 1 1/2 gigahertz, then three will correspond to about 550 megahertz.

Now, if I rotate the polarizer even more to block out the first laser frequency I showed you before, I up with only this frequency of the laser over here. There we are. So then, again, just it's a matter of adjusting then the polarizer to have either one frequency go to the Fabry-Perot or the two frequencies simultaneously. Right now we have both of them simultaneously incident on the Fabry-Perot interferometer. Again, as you can see, the separation is 550 megahertz.

Now, the width that you see here, it has nothing to do with the laser line width. It is determined by the width of the scanning Fabry-Perot interferometer. Of course, if the laser jitters a lot, then you would see the width of the laser here. But right now, the width of the scanning Fabry-Perot is much bigger than the width of the individual laser oscillations.

Now we're ready to look at the beat frequency between these two modes. So we need-- for this, we need a wide band detector that can measure a beat note much bigger than, or at least as big as 550 megahertz. The setup is over here.

Here is the laser again. And the output of the laser, again passes through the polarizer. And then we take a little bit of the light through this beam splitter here and reflect it by this mirror and onto this lens. And this lens here will focus the light onto this fast detector. And that's how we're going to measure the beat frequency between the two lasers.

So now, let's look at the output of the electronic spectrum analyzer here on the scope. Now, on your screen you see-- in the lower part of the screen, you see the output of the scanning Fabry-Perot interferometer where we show you the two frequencies of the laser separated by 550 megahertz. And in the upper part is the output of the electronic spectrum analyzer where the scale is 20 kilohertz per box. And the center frequency over here is 557 megahertz, which is close to what we estimated from the scanning Fabry-Perot. The resolution here is three kilohertz.

All right, so now what I'm going to do, just to make sure that, indeed, this beat output is coming from the laser, what I'm going to do now is rotate the polarizer to get only one frequency and see if we can extinguish the beat. So, as you see on this screen here, I'm going to be then extinguishing one of the modes that enters the fast detector and also the scanning Fabry-Perot. And as we watch over here the output of the electronic spectrum analyzer and see it gets smaller and smaller until we have nothing at all.

So here we are. There's only one frequency oscillating in the laser. And there is no beat. All right, so now let me bring up the other frequency. Now we have two of them, then, going into the detector and into the scanning Fabry-Perot. And we get back our beat frequency centered on 557 megahertz.

All right, now this resolution is not so wonderful. And it's limited by the setting that I have used on the electronic spectrum analyzer. What I'm going to do now is I'm going to change to our highest resolution of 200 Hertz per box with a resolution limit of 30 Hertz.

Here we are. Now we have 200 Hertz per box and a resolution of 30 Hertz, which I hope you can see. Now I'm going to have single sweep scans to look at the spectral width of the two lasers. So here we go.

So here we are. We can see that, again with a scale of 200 Hertz per box, and the resolution is 30 Hertz, we see that the spectrum that we can observe is indeed very close to the instrumental line width of 30 Hertz.

So we have demonstrated that the intrinsic line width, the fundamental line width of a laser must be pretty small, certainly smaller, quite a bit smaller than 30 Hertz. So remember here is the beat we looked at the spectral width of the beat note of two lasers. So each one must be quite a bit smaller than 30 Hertz. If we had a better technique for doing the spectrum analysis, we would have shown you an even narrower spectral width.

Now just as a footnote, what I'd like to do is calibrate the electronic spectrum analyzer for you by bringing in a good stable oscillator around 557 megahertz or so and indeed demonstrate that the 30 Hertz is really the resolution limit of the electronic spectrum analyzer. So when you come back, we'll have that set up for you.

So here is the stable oscillator over here. It's an HP stable oscillator. And the output at 557 megahertz or so, we're going to feed it into the electronic spectrum analyzer to see what the width is. So here I pressed the single sweep button. And here is the output. And you can see that the width here is very similar to what we saw for the beat between the two laser frequencies. And this shows that, indeed, the resolution limit is 30 Hertz of the electronic spectrum analyzer.

So, in summary, the laser spectral width depends on the stability of the laser cavity. If the laser cavity jitters and shakes, or the refractive index fluctuates, then we would expect that the laser spectral width would be quite broad. So in order to reduce the laser spectral width, we need to design a stable laser cavity.

Now, in terms of typical numbers, a simple helium neon laser like the one we used in this demonstration, the line width would be around 50 kilohertz or so. The recently developed CW neodymium YAG lasers have a line width of the order of 1 kilohertz. But other lasers like semiconductor lasers, dilasers, and what have you can have line widths of many, many megahertz.

Now remember, the intrinsic line width is only a small fraction of a Hertz, or, as I mentioned before, of the order 10 to the minus 3, 10 to the minus 4 or even smaller. Now, there are not many applications that require such narrow line width, except one. And that is the ring laser gyroscope that's used for navigation. Now, for this application, the intrinsic line width of the laser is at present the limit on the ability of this device to measure inertial rotation. But many other applications, at present, do not require that super narrow spectral width that is inherent in the laser.