SHAOUL EZEKIEL: In previous demonstrations, we showed the laser beam to be a very simple beam with a single spot in the transverse direction. Now, most lasers actually put out a beam like that-- just one spot in the transverse direction, and the intense distribution is Gaussian. It has very nice properties, and that's why it's a very popular beam from a laser.

Now, a laser can also put out other intense distributions because of the existence of transverse modes, which means that the beam would look very spotty. Sometimes it can look like a doughnut with darkness in the center. You can also make it look like two spots, three spots-- you can make it look like a flower and so on, all because of the existence of transverse modes.

Now, in this demonstration, we've got a special laser for you that can exhibit these transverse modes. And the setup is here. We have our usual discharge tube. Except in this case, the bore diameter is a little bit bigger than in previous demonstrations. The diameter here is of the order of 2 millimeters-- 2 and 1/2 millimeters or so. While before, the bore diameter was about 1 and 1/2 millimeters.

One mirror is attached to the discharge tube over here. And the other end of the discharge tube has a Brewster window so that we can place the second mirror over here. This mirror here is curved about 60 centimeters of a radius of curvature, and the mirror here is a flat one. The transmission of the mirrors is very small, and so that the output light is not going to be as bright as we would like it. But hopefully, we'll be able to see the transverse modes.

The beam, then, from the laser will come out over here. And then we'll reflected by this mirror, and then this mirror into a lens. Here, we expand the beam. And then the expanded beam then will fall onto the screen over here.

So now, let me turn on the laser. And then we count up to 7 or 8 seconds or so, and here is this laser on. And the output, then, from the laser is weak, I know, but you might be able to see it.

Here's the output from the laser. And then we're going to reflect it, as I said before, by this mirror, this mirror, to the lens, and then onto the screen. And now we'll have one camera look at the screen so we can look at the transverse modes, and another camera can look at my hands adjusting one of the mirrors to change the number of modes and the intensity distribution that you will see on the screen.

Now here, as you can see, the beam looks like a doughnut mode with no field in the center. And my hand, you can see in the lower right-hand corner, adjusting the mirror mount. Now here, I'm going to start now adjusting. And then you can see that the intense distribution varies-- varies quite a bit.

Here we are. Here you can see a very complicated kind of pattern. Here's another one with two dark spots-- single dark spot. And here it looks like a flower. Nice, pretty little patterns. And these are all due to these transverse modes.

Now, what you're seeing here is a mixture of transverse modes. They're not necessarily pure ones. That means just a single transverse mode by itself.

Now here, if I'm misaligned too much and get rid of most of them, here is our lowest-order mode, which is called the 00 mode. Now, here is the normal kind of laser beam. But in this particular laser setup, I can generate all kinds of other intense distributions, due to the other transverse modes that can be generated in this kind of setup with a larger bore in the discharge tube. It's very pretty, as you can see.

Now, as I mentioned before, in most lasers, one wants to get rid of these transverse modes so that we can only have the 00 mode. And when we come back, we're going to show a method of eliminating the lasing of these transverse modes, other than the lowest-order one. We're going to do this by placing an aperture-- a small iris inside the laser cavity.

We have now placed an aperture inside the laser cavity, so as to get rid of all transverse modes except the lowest-order one-- the 00 mode. The aperture is over here. When we're placing it in the space between the Brewster window and the second mirror.

So here's the aperture. And then by adjusting this knob here, I can then change the size of the aperture. In the meantime, we've also covered the laser tube here with some white paper so that we don't have too much light to burn the camera. So in case you don't see the discharge tube so well as before, it's because we've covered it up. So now let's look at the screen now to see the transverse modes without the aperture stopped down.

Here we are. We see those transverse modes or mixture of transverse moles now what I'm going to do is I'm going to now reduce the size of the aperture. And let's see what happens. Here I am reducing it. And you can see as we go back a little bit, here's some other modes. And then when I stop it, way down to about a millimeter or so, you can see that I have now the lowest-order mode-- the 00 mode.

Let's do it again. Let me open it up again. Here is the transverse mode, and then I stop it down. I get rid of all transverse modes except the lowest order. In fact, now I can even adjust the mirror. I can adjust the mirror, and indeed, I can't move the spot around, but I don't get any transverse modes showing up.

So in summary, then by putting a small aperture inside the laser cavity and choosing the diameter appropriately, we can get rid of all transverse modes except for the lowest-order mode. Now, most commercial lasers either have an aperture like that inside the laser cavity, or have the bore size of the laser amplifier so chosen so that only the lowest-order mode would lase, and would by very difficult to have the other transverse modes lase also. And that's why most commercial lasers put out that lovely single-spot beam.

Now, another interesting thing about transverse modes is that their frequencies are different from one another. And that depends on, again, the length of the cavity and the curvature of the mirrors. So when we come back, we're going to have the spectrum analyzer set up so we can look at the frequencies of the various transverse modes.

We're now ready to look at the frequencies, or the spectrum, of the transverse modes of this laser using a scanning Fabry-Pérot interferometer acting as an optical spectrum analyzer. And here is the set up. The output of the laser-- now we take the output from the other end-- from the other mirror. We're going to reflect it by this mirror here, this mirror here, onto this scanning Fabry-Pérot interferometer.

The length of the cavity is about 10 centimeters, which means that the free spectral range will be about 1 and 1/2 gigahertz. The output of the scanning Fabry-Pérot interferometer then goes onto the scope to display the frequencies of the laser. Now we're going to look at the intensity of the beam, or the transverse intensity distribution of the beam showing the various transverse modes. And at the same time, we're going to look at the spectrum of the laser light as measured by the scanning Fabry-Pérot interferometer.

Now, here on the screen now we see-- on top, we see the intense distribution of the laser-- the transverse intensive distribution. And below, we see the corresponding spectrum. What I've done here is I've stopped down the aperture so that we only have the lowest-order mode-- the 00 mode oscillate. And on the scope, we see three or four modes due to the longitudinal modes oscillating in the laser.

And of course, the number of longitudinal modes will depend on the width of the gain medium. The laser is about 40 centimeters long, which means that the mode spacings are about 375 megahertz. And that's why we get three and sometimes four modes oscillating within the bandwidth of the amplifier, which is 1 and 1/2 gigahertz.

And just for fun, what I'm going to do is tap on the mirror gently to shake the cavity. And you can see the contour of the bandwidth of the amplifier, which is about, as I said before, around 1 and 1/2 gigahertz. So when I'm not shaking the cavity too much, then we see the longitudinal modes stable and quite clearly.

So now what I'm going to do is open up the aperture-- introduce some high auto modes. So what I'd like you to do-- look at the picture above. And then at the same time, look at the spectrum. So I'm just slowly going to bring in--

Now you can see already here, even though it still looks like-- it appears to be just the lowest-order mode, but it isn't. Because if you look at the spectrum, you see that we have introduced some new frequencies. And these new frequencies are associated with the transverse modes that are now oscillating. And I can go further now and open up the aperture some more. Here we are.

So now, you can definitely see a number of high-order modes. And look at the frequencies now. There's lots of them. And again, they're within the bandwidth of the amplifier. There's one thing nice about having a lot of transverse modes is that you can have a lot more power coming out from the laser, because you have more modes oscillating.

So here, I'll do it again. I'm going to reduce the aperture size and to get the lowest-order mode oscillating-- see again, they just get the longitudinal modes of the 00 mode. And now I will introduce the transverse modes again, to show that they have-- their longitudinal mode frequencies are different from the 00 mode.

So far, I've only been able to show you a mixture of transverse modes. In fact, the only isolated mode that I was able to show you was the lowest-order one, the 00 mode, by itself. And then I showed you a mixture of transverse modes. Now, in the next demonstration, I'm going to use a little trick to isolate a single higher-order transverse mode so that we can look at it, and then we can also look at its spectrum.

Now, in order to isolate one high-order transverse mode, I'm going to use a very thin wire. The wire, we'll place along the vertical direction inside the laser cavity. And in this way, we'll be able to prevent the lowest-order mode, the 00 mode, from oscillating, because we'll place the wire right in the center of the 00 mode, so it's providing a lot of diffraction loss for it.

But for the next high-order mode, the two-spot mode, so-called 1 0, 01, depending on how you count these modes, then one will be able to oscillate if the wire's thin enough, because this wire is going to be placed right where the field is 0. Now, to make that clearer, I'm going to show it to you on the screen. Before I do this, I want to show you where the wire is placed.

The wire is placed in a holder here, and the wire is about 50 microns wide. And you place it vertically inside the laser cavity. I have an adjustment here. I can move the wire in and out in a horizontal direction. And also, I have another adjustment here that rotates the orientation of the wire from, let's say, vertical to horizontal. Now let's go look at the screen and see what sort of transverse mode I've been able to isolate.

Now, here on the screen, you see that I've isolated the next transverse mode. It's called either 01 or 1 0, depending on how you count these modes. And this consists of essentially two spots with 0 field in between. And remember, I used a vertical wire right in the center of the mode so that this particular transverse mode doesn't need any gain in the middle, and therefore can oscillate with the wire in place. But most of the other modes, like the lowest-order mode and so on, cannot oscillate with this wire in there, because that provides too much diffraction loss. And that's why we've been able to isolate this one particular mode like this.

Now, if we look on the output of the spectrum analyzer, as shown on the oscilloscope below, you can see that we have two and sometimes three modes that correspond to the longitudinal frequencies of this transverse mode, just like in the case of the 00 mode-- just clean, single transverse mode. Now, what I'm going to do now is adjust the wire, or translate it horizontally so that I can bring in other modes. So now, I'm going to move it a little bit.

Now you can see I brought what we call the 02 mode. It's a little faint, but that's what I'm able to do right now. And you can see on the scope below that, again, it's clean mode. But of course, the intensity is weak. Now let me go in the other direction, back again.

Here we bring in the 01 mode. And now let me go further-- get the wire out of the way of the cavity. And now you can see that I'm bringing in other transverse modes.

Difficult to tell from the intensity distribution-- just looks like a blob. But below, the frequencies-- you can see I'm bringing in other modes. And here I go further. And that's what it is. Now let me go back to the 1 0 mode.

Here I am-- 1 0 mode. And then over here, which is the 2 0, or 02, depending, as I say, how you count them. And now I'm back to the mixture of transverse modes. Now, the frequencies of the transverse modes depend on the length of the cavity and the curvature of the mirrors.

And under certain conditions-- for example, in the case of a confocal cavity where the rays of curvature of the mirrors are identical and equal to the spacing in the cavity, you can get all the even modes under the 00 mode, and all the odd modes halfway in between. And for a plane-- another example is for a plane mirror cavity, the frequencies of all transverse modes are degenerate-- are identical. But if you're not confocal and you're not plain plane, then you can expect transverse modes all over the place.

So so far, I've shown you that by using a simple thin wire placed in a vertical direction inside a laser cavity, we were able to isolate one of the transverse modes-- the 01 or 1 0 mode. That's the one with the two spots side by side. Now, if I took this wire and I placed it along the horizontal direction inside the cavity, I would be able to isolate the other transverse mode that has the two spots, one on top of the other.

Similarly, if I place the wire at 45 degrees, I would have the two spots inclined at 45 degrees. Just in case you don't believe me, I'm going to do this right now. So let's look at the screen while I rotate the wire by a few degrees at a time, and then pick it up-- pick up the horizontal position of the wire.

As you can see, the two modes are beginning to get inclined. I'll do some more. Here we are. It's almost 45 degrees or so, following the orientation of the wire. So here we are. We see the two modes now are inclined at an angle close to 45 degrees.

Now let me see. If I adjust the translational position of the wire, let's see what happens to the next high-order mode, where here we are. The 02 or 2 0-- you can see that that one is also inclined at the same angle as the 01 mode. Now let me go back to that one and back to this one.

And indeed, you can see that I have a pure mode, because the spectrum below shows that I have only the longitudinal modes associated with one transverse mode. Now, in practice, I could place all kinds of structures inside the laser cavity and isolate almost any transverse mode I want. May get complicated, but in principle, it can be done.

Now, in this next demonstration, we're going to have some fun. We're going to start with the laser oscillating in the 01 or 1 0 transverse mode. Then, I'm going to take a knife edge or a razor blade, like this, and I'm going to place it inside the laser cavity to block only one of the spots-- one of the lobes of this transverse mode-- and see if the laser can still oscillate on one lobe.

All right? So I'm going to take this, then-- this knife edge, and I'm going to place it here inside the laser cavity. And as I'm doing it, maybe we can look at the screen.

And here we are. We have the 1 0 or 01 mode. Then I'm going to bring this knife edge up close. Here we are. And now, it's not interrupting anything. But now, I'm going to move it in to cut one of the lobes out. So I'm going to do it slowly.

Oops. Too fast. Now I'm going to start again. Now you can see that as soon as I get close to these lobes, the entire mode drops out or stops lasing. I cannot just have the laser oscillate only in one of the lobes.

And this shows that indeed, this is a transverse mode of the laser, because I cannot separate them. They go together. I cannot just have one and not the other.

Now, what's going to happen if I take this knife edge and place it outside the laser cavity and try to block one of the modes when the mode has already left the cavity? So this is an interesting question. So I'm going to take it out from here, and then I'll place it outside the laser cavity. And then we'll see what happens then.

Here we are outside the laser cavity. Now I'm going to put the knife edge over here. Let me first adjust it so I'm close to the beam. Oh, right about here. Now let's look at the transverse mode. As I cut with this knife edge, I cut into the transverse mode.

So here we are. You see above the transverse mode. Now let me start coming in with a knife edge, and let's see what happens. So what you see happens is that we get rid of one lobe, and the other lobe is there. If I cut in some more, you see the-- starts to distort a little bit, starts to get bigger. And then we go back.

Here it is by itself. And then here is with the knife edge outside the beam altogether. And we have the transverse mode by itself. Again-- let's do it again. I come in. I can cut one side lobe, and it still is an intensity left. And then as I cut in some more, you can see that the other lobe gets wider.

So that's very, very interesting. When I did it inside the cavity, the mode actually just got extinguished. It could not lase. But when I did it outside, I still have light propagating, even though I cut one of the lobes out. Now, to actually calculate what happens to the intensity distribution, or the field distribution

When I do that, is a little complicated, because it's not just that I remove one of the lobes. It's a lot of diffraction issues that one has to consider. And just like any complicated problem, we leave it as an exercise to the viewer to calculate what actually happens to the field distribution when I place a knife edge in the beam when it's outside the laser cavity.